DRIVER BEHAVIOUR AT HORIZONTAL CURVES

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List of errata

Page i, line 29 :
replace "(except one)"
with "(with the possible exception of one)"

Page 68, line 18 :
replace "curves less than ..."
with "curves with radii less than ..."

Page 70, line 12 :
replace "DMR" with "New South Wales DMR"

Page 80, line 4 :
replace " (144 km)" with " (14.4 km)"

Page 81, line 5 :
replace "were from" with "involved"

Page 110, page 23 :
replace " (61 mm)" with " (61 cm)"

Page 173 :
replace "Table 3.7 Proportion Encroaching ..."
with "Table 3.7 Proportions (%) Encroaching ..."

Page 177, lines 3-4 :
replace "Lane Only Lane & Sealed Shoulder"
with "Lane & Sealed Shoulder Lane Only"

Page 196 :
replace "Scale 1 : 400" with "Scale 1 : 2500"

Page 222, line 14 :
replace "39% more ..." with "30% more ..."

Page 246, line 8 :
replace "Figures ... 4.42" with "Figures ... 4.43"

Page 252 :
replace "Table 4.5 Proportion Encroaching ..."
with "Table 4.5 Proportions (%) Encroaching ..."

Page 276, lines 9-11 :
replace "roadway width. The ...realignment."
with "roadway width at the Leithfield BS curve. The lateral separation at the curve mid-point seems to have not changed as a result of realignment at the Foremans Road curve."

Page 288, line 12 :
replace "Department of Main Road"
with "DMR, New South Wales"

Page 289, line 4 :
replace "Report pp" with "Report No."

Page 292, line 20 :
replace "pp. 469-484." with "pp. 441-468."

ABSTRACT

Studies relating accident occurrence to horizontal curve geometry indicate a strong association between the radius of horizontal curves and accident occurrence, but the individual effect of horizontal curvature on safety is still uncertain. The preponderance of human error as a contributory cause of accidents has led to a growing interest in research on driver behaviour. The human factor in road safety is discussed and literature on driver behaviour on horizontal curves is reviewed.

A study involving unobtrusive observation of driver behaviour at two curves (an isolated curve and a reverse curve) before and after realignment was carried out. Data on driver behaviour was collected by continuous video-recording of each subject vehicle as it moved through each curve. Lateral placement and speed data along the curve were extracted from the video record, and the path radius and sideway force coefficient at the mid-point of the curve were estimated. The observed driver behaviour is discussed.

The results of the study were checked against the underlying design assumptions, which are shown not to be completely and universally valid. The evaluation of the realignment, based on driver behaviour and the sideway force coefficient, and the accident records show that there was an overall improvement in the margin of safety at all the curves (except one). The results do not support the concept of risk homeostasis, although there is evidence of risk compensation. SEE ERRATA

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CHAPTER I

1.1 ROAD SAFETY IN NEW ZEALAND

1.1.1 Road Accidents in New Zealand

Every year in New Zealand, hundreds of people are killed and many thousands more injured as a result of road accidents. In 1986 alone, there were 13,383 reported road accidents resulting in 767 fatalities and 18,758 injuries (MOT, 1986). These figures represent only a small part of the overall road accident occurrence. Comprehensive hospital-based surveys have indicated that only about half of injury road accidents are reported to the Ministry of Transport (MOT, 1974; Bailey, 1984; Bailey, 1985), even though a motor vehicle driver involved in any road accident resulting in death or injury to any person is required by law to report such an accident to the Ministry of Transport within 24 hours. No official statistics are available for non-injury property-damage- only (PDO) accidents. It is estimated, on the basis of insurance company records, that reported accidents represent only 10 percent of all road accidents (MOT, 1974); a recent study involving a survey of vehicle insurance claims produced a sample (n = 3838) with a ratio of 1 injury to 14 non-injury accidents (Murray-North Partners Ltd, 1983). Hence the accident involvement rate is much higher than official statistics might suggest. In economic terms, Brown Copeland & Co Ltd (1986) estimated the total cost of road accidents in New Zealand to be 510 million dollars in March 1983 prices, and official statistics accounted for only 40% of this total cost.

Examination of reported accident statistics shows that the number of road accidents, fatalities and injuries have been on an upward trend since 1979. Jones and Frith (1988) analysed reported accident statistics for the 1980-86 period and showed that there was an increase of 30% in fatal accidents, a 2% increase in serious injuries and a 70% increase in minor injuries over this period, with the increases occurring mostly on open-speed roads. They also identified the 'lost control on bend' accidents to be the most common accident type for both fatal and injury accidents, and especially on the open roads where 'lost control on bend' accidents accounted for a third of fatal and injury accidents. As a comparison, the statistics for lost control accidents on the open roads (i.e. rural areas) are as shown in the following table.

Year	**Fatal** (Straight)	**Fatal** (Curve)	**Injury** (Straight)	**Injury** (Curve)
83	43	344	503	924
84	45	360	485	1041
85	40	402	569	1144
86	57	407	608	1282
87	59	456	652	1408

Table 1.1 Lost Control Accidents on Open Roads

Analysis of data for New Zealand state highways (as extracted from aerial photographs) shows that there are over 7000 km of straight road compared to less than 3500 km of curves. This implies that lost control accidents are disproportionately represented on curves.

1.1.2 New Zealand's Road Safety : An International Comparison

The problems involved in comparing international data on road safety has been addressed by Appleton (1982) who identified major difficulties in correcting for differences in accident data collection, procedures, transport conditions and stages of economic growth. Appleton concluded that the best statistic to use is fatalities per vehicle kilometre travelled (VKT) and showed that from a comparison of 17 countries with compatible data for the year 1982, New Zealand's road safety is ranked in the middle position. However a comparison of fatality rates with some other developed countries over the last 20 years (1965 to 1985) shows that New Zealand's safety performance is falling behind those of other comparable countries (Barnes, 1988).

1.1.3 Road Safety Research in New Zealand

In recent years, much attention has been directed towards finding solutions to road safety problems. This increased emphasis is partly because road safety is being recognized as a significant social and economic problem for the country. Of equal importance is the fact that the New Zealand road transportation system is now relatively mature (the rate of infrastructure development is much lower than in the past) and the time has come to fine-tune the system to make it safer and more efficient.

Road safety research in New Zealand is co-ordinated by the Road Traffic Safety Research Council (RTSRC) which works closely with the Ministry of Transport as well as various funding organizations in pursuing all relevant research into road safety. The RTSRC annual reports give an appreciation of the increasing emphasis on road safety research activities in New Zealand; for example, the 1988 annual report listed 89 safety related research projects, compared to 36 in the 1978 listing. In general, road safety research in New Zealand falls into four categories: accident statistics and analysis, human factors, environmental factors and vehicle factors. It is not the intention of this thesis to further delve into the spectrum of road safety research except to mention that this project is in the area of human and environmental factors.

1.2 HORIZONTAL CURVE : GEOMETRIC DESIGN

Horizontal curves are roadway elements where changes in road direction are made. A horizontal curve provides the link between two tangents (an isolated curve), a tangent and another curve or between two curves. Horizontal curves can be fully transitional, fully circular or circular with adjoining transitions, and usually involve some degree of superelevation.

Horizontal curves become an integral part of the roadway mainly because of constraints imposed on road layout by topography and land-use. Nowadays, however, horizontal curves are purposefully inserted along long stretches of tangent sections to reduce monotony to the drivers. Horizontal curves also improve perception of speed in oncoming vehicles, as well as reducing glare from opposing vehicles during hours of darkness.

The geometric design of horizontal curves is concerned with the horizontal alignment of the roadway. The elements of design comprise, where appropriate, the radius of the central circular arc, the superelevation, the length of spiral transition curve, pavement widening and lateral clearance on the inside of the curve for ensuring adequate sight distance across the curve.

The design of the central circular arc is governed by the basic equation:

$$e + f = (v^2)/(gR) \quad \text{......................} \quad (1.1)$$

where,

e = superelevation,

f = sideway force coefficient, SFC

v = vehicle speed

R = radius of curvature of the horizontal curve

g = acceleration due to gravity

This equation has been derived from a consideration of the mechanics involved in a vehicle traversing the circular arc.

An excellent review of the development of horizontal curve design is contained in ARRB Special Report No. 15 (Good, 1978). In using equation (1.1) the aim of the designer is to determine values of the radius of curvature (R) and superelevation (e) which also satisfy the constraints on the sideway force coefficient (f) and the stopping sight distance, while using the vehicle speed as the overall control.

The choice of vehicle speed for design has traditionally been based on the prevailing topography and the class of road (AASHO, 1954; NRB, 1960). A constant speed value is usually assumed for a section of highway with similar topography and classification and this speed value, commonly referred to as the design speed, is used to correlate the geometric elements of the highway. Recent studies at the

Australian Road Research Board (McLean 1978) have indicated that driver speed behaviour can be related to the standard of the geometric elements (principally horizontal curves) and the road environment (principally terrain), and accordingly, an alternative approach to road design has been adopted by the National Association of Australian Road Authorities (NAASRA 1980). A major difference between the traditional approach and the NAASRA approach is that the former generally assumes a constant speed value for design while the latter considers the influence of alignment standard on driver speed behaviour, thereby also necessitating an iterative method for arriving at the final design.

Superelevation at the central circular arc helps to counteract some or all of the centrifugal force of a cornering vehicle. The range of superelevation values is usually between a maximum of 0.10 and a lower bound equal to the normal crossfall on straights (typically 0.03). Values higher than 0.10 are not normally used because of stability problems for highly laden vehicles and the tendency of slow moving vehicles to track towards the centre of the curve.

Sideway friction is responsible for bridging the difference (within available friction supply) between the centrifugal and superelevation effects. The available friction supply is dependent on the road surface conditions, the condition of the tyre and the speed of the vehicle. The typical friction capability assumed by AASHO (Glennon, 1969) is in the range of 0.45 at 30 km/h to 0.27 at 120 km/h; measurement of skid resistance using the M.L. Mu-meter at eight sites in Auckland, New Zealand (RRU, 1977) shows the sideway force coefficient varying from 0.65 at 32 km/h to between 0.65 and 0.40 at 96 km/h (where there is good macrotexture, speed increase has little effect). The sideway force coefficient used for design is set by the New Zealand standard (NRB, 1955), and ranges from 0.2 at 20 km/h to 0.08 at 160 km/h.

An integral part of horizontal curve design is fitting transition curves. It has been general practice that horizontal curves on open roads in New Zealand are designed with some form of transition curves. A transition is a curve of varying radius between the tangent and the circular curve in order that the centrifugal force may build up in a gradual, uniform manner. The transitions also provide sections of road over which superelevation and/or pavement widening may be gradually applied, as well as improving the aesthetics of horizontal curves. A wide range of curve forms are suitable for transitions. Two types in common use on New Zealand roads are the cubic spiral and the lemniscate. In recent years, the cubic spiral has become more dominant mainly because of its incorporation within computer programs for geometric design (e.g. ICES ROADS and COGO).

Horizontal curves may be widened to maintain the lateral clearance between meeting vehicles at a level equal to the clearance on straights, as vehicles on horizontal curves occupy a greater width than on straights. The amount of widening depends on the design speed, pavement width (on straights) and the geometric radius of the curve.

Apart from designing horizontal curves for safe passage under normal conditions, provision is also made to ensure that drivers are able to perceive any road hazard ahead in sufficient time to identify and take appropriate actions. The safe stopping sight distance (SSSD) is a theoretical stopping distance, measured along the travelled lane, for a driver with an eye height of 1.0 m and an object (hazard) height of 0.15 m, and allowing a driver perception-reaction time of 2.5 seconds (NRB, 1960).

The above discussion of the various parameters of horizontal curve design gives an introduction to the basic ideas involved in the design. A brief discussion is warranted to point out the problems faced by the road designer, while using the subject of horizontal curve design as an example. Good (1978) has observed that current policies on horizontal curve design have been developed without the aid of direct observation of road user behaviour. This implies that the design is in many respect based on the designer's expectation of the driver's behaviour which could very well be different from the actual on-the-road behaviour (for example, the speed behaviour at curves, discussed previously in conjunction with design speed). The designer hypothesizes a model of driver's behaviour (e.g. wheel path radius equal to geometric radius and constant speed inside the curve) and relies upon the laws of mechanics as a technique of design. However the road user's driving behaviour is a result of judgement based on an interaction of factors such as motive, attitude and experience. The technicalities of using the road is also generally 'learned' through experience rather than through an analytical examination of the underlying mechanics involved. It is therefore not adequate to model driving behaviour through merely understanding the mechanics of road design. Rather, an empirical approach involving systematic observation of driver behaviour is necessary to provide the designer with a better idea of road user's behaviour.

Apart from the problem of a designer's expectation not matching actual user behaviour (a result of insufficient driver behaviour research), a road designer has to work in a situation where there is relatively little control over the variability in the driver's behaviour (unlike typical of engineered structures where the designer has good control over the materials). This variability of driver behaviour is difficult to control because behaviour varies from person to person and operates in a transient manner within each indiviual. Stringent screening of users similar to that for airline pilot could solve much of the problem but such a step is both politically and socially unacceptable, given the importance being placed upon the road transport as a mean of mobility.

Within the present state of knowledge of driver behaviour, the current approach to road design is to set a limiting value on this behaviour and design within this limit in accordance with a hypothetical model of driver behaviour. A safety factor is also incorporated into the design. For example, in horizontal curve design, drivers are assumed to negotiate the curve with a path equal to the as-designed geometric radius. A limiting speed value is used to decide on values of superelevation and geometric radius on the basis of the assumed steering behaviour. The safety factor is the difference between available and design side friction. The limited knowledge of driver behaviour implies that it is not clear how limiting values for design are related to the threshold of the behaviour under consideration. The assumption of a driving behaviour model that is different from on-the-road behaviour means that the safety factor on the road could be very different from the design value. There is an obvious need to have a better understanding of driver behaviour. A useful area of study is to do field observation to assess the discrepancy between the 'observed' and the 'as-designed'.

1.3 ROAD SAFETY STUDY

The study of road safety can be conveniently grouped into the three areas that reflect the major components in the road transportation system (namely the driver, the vehicle and the environment). There have been many studies carried out concerning the interaction of each of the components as related to road safety. Research into the design of vehicles, such as crash-worthiness and road handling characteristics, have contributed to an improvement in the safety standard of modern road vehicles (SAE Handbook). There have been significant changes in the design and operations of traffic controls and roadway elements (FHWA, 1982). There has also been a big increase in the quantity and quality of research concerning the driver behaviour (Naatanen and Summala, 1976; Shinar, 1978).

A frequently used approach in the study of road safety is the statistical analysis of reported accident statistics. One method is to measure accident occurrence based on a model of the form:

Safety = level of accident occurrence
= risk x exposure

Broadly speaking, there is general acceptance of the utility of the risk and exposure concepts in studying road accident involvement, but there is no general agreement as to how risk and exposure can best be defined (Wolfe, 1982; Hauer, 1982; Haight, 1986). The traditional approach is to express the accident rate as the number of accidents per unit exposure (of time, distance, population, or some combination of these) and use this as accident risk. The most common form is the number of accidents per vehicle kilometre travelled.

Statistical analysis has frequently been used (Council, 1978) to correlate accident data with variables describing the roadway, the vehicle and/or the driver. The primary goal in these 'mass data' analyses is to identify relationship among the variables, and can be broadly grouped into two types : descriptive (or comparative) studies and predictive studies. A descriptive study involves grouping of accident data into various categories of interest and combining accidents with some measure of exposure so that rates can be examined within the categories, and generally involves cross tabulation. Predictive equations, usually developed using a regression technique, provide information concerning how changes in the explanatory variables affect the dependent variable (accident rate, crash severity or proxy measures of safety).

Another frequent use of accident statistic is for the evaluative studies of counter-measures, which typically involve a before-and-after design. The emphasis here is on whether or how effective the implemented change has been in bringing about the desired result.

Notwithstanding the mechanics involved in the statistical analysis, there are several aspects of road accident statistics that warrant some attention. They include:

(a) the not-always-consistent definition, across national boundaries, of accident type and accident severity, as well as the type of associated variables that are collected;

(b) inconsistent data due to varying reporting thresholds across different jurisdictions and between different accident types and severity;

(c) inconsistent data due to failure to investigate e.g. during busy periods;

(d) biases in accident data such as estimating accident location or vehicle speed before collision, and assigning the causes of road accidents based on 'best' judgement.

Hence reported accident statistics are neither totally reliable nor completely consistent. However, since accidents are very rare events and because it is not possible to experiment with accident events, the extensive accident statistics which have been routinely collected over many decades provide a common source of information for many road safety studies, and particularly mass data statistical analyses.

1.4 ACCIDENT OCCURRENCE ON HORIZONTAL CURVES - A LITERATURE REVIEW

Past research on the relationship between horizontal curvature and accident rate on two-lane rural highways is reviewed. Most studies have indicated that the accident rate increases as the radius of curvature decreases i.e. sharp curves are more hazardous. The studies are reviewed in chronological order.

The magnitude of a curve is expressed either in degree or radius of curvature. The degree of curvature is defined as the central angle subtended by an arc of 100 feet. If R and D are radius and degree of curvature respectively, then

$$R = 5729.6/D \text{ (R in ft)}$$

In this report, a sharp curve is a curve with a small radius of curvature. Conversely, a flat curve is one with large radius of curvature. A curve that turns to the left (from the drivers' perspective) is a left curve or left-turning curve, and one that turns to the right a right curve or right-turning curve. It is important not to forget that drivers travel on the right side of the road in America whereas in New Zealand, Australia, U.K. and other countries, drivers travel on the left hand side of the road.

1.4.1 Raff Study

It is appropriate to begin this review of horizontal curvature and accident experience by referring to the classical study by Raff (1953), whose work on road geometrics and motor vehicle safety has been extensively quoted. In the study, 15 states in the U.S.A. provided information covering one year (1941) for 16421 accidents on about 5000 miles of main rural highways. Factors studied included the number of lanes, average daily traffic (ADT), degree of curvature, frequency of curves, pavement width and shoulder width. Accident data were merged by applying a weighting factor to each state's data (Type 1), by selecting those states whose reporting met a certain standard (Type 2), and by including all data without adjustment (Type 3). The unadjusted accident rate (Type 3) was found to be "most reasonable".

Raff's results indicated that accident rate increased as curves became sharper, on all types of

ACCIDENT RATES ON CURVES, BY DEGREE OF CURVATURE AND ROADWAY TYPE

Curvature	Two-lane roads		Three-lane roads		Four-lane roads: Undivided		Four-lane roads: Divided		Four-lane roads: Controlled access	
	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles
Type 1 accident rates (All states, using adjustment factors)										
Degrees										
0 - 2.9	504	2.6	11	5.6	98	4.9	95	2.4	180	2.4
3 - 5.9	596	3.6	11	9.8	90	8.4	65	4.2	162	3.4
6 - 9.9	338	3.6	6	14.1	16	7.9	5	11.9	38	5.6
10 or more	354	4.8	11	38.0	3	5.8	12	30.6	0	-
Type 2 accident rates (Selected states, without adjustment)										
0 - 2.9	340	1.8	0	-	43	1.9	33	0.7	180	1.6
3 - 5.9	447	2.5	0	0.0	33	2.1	52	2.7	162	2.3
6 - 9.9	287	2.9	0	-	10	2.9	1	1.2	38	4.5
10 or more	281	3.4	1	10.0	0	-	0	-	0	-
Type 3 accident rates (All states, without adjustment)										
0 - 2.9	504	1.6	11	1.7	98	1.9	95	1.8	180	1.6
3 - 5.9	596	2.5	11	2.8	90	2.6	65	2.4	162	2.3
6 - 9.9	338	2.8	6	3.5	16	3.3	5	3.1	38	4.5
10 or more	354	3.5	11	7.3	3	1.2	12	6.7	0	-

Table 1.2 (Raff, 1953)

ACCIDENT RATES ON TWO-LANE CURVES, BY DEGREE OF CURVATURE AND FREQUENCY OF CURVES

Frequency of curves	Curvature: 0 - 2.9°		3° - 5.9°		6° - 9.9°		10° or more	
	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles
Type 1 accident rates (All states, using adjustment factors)								
Number per mile								
0 - 0.9	128	3.0	110	5.4	13	4.2	31	8.9
1.0 - 2.9	178	2.3	163	3.7	96	4.5	53	4.2
3.0 - 4.9	125	2.1	223	2.9	170	3.3	139	4.3
5.0 - 6.9	75	3.3	100	3.2	59	2.8	130	4.6
Type 2 accident rates (Selected states, without adjustment)								
0 - 0.9	42	1.6	47	3.2	2	1.1	4	1.4
1.0 - 2.9	105	1.4	97	2.1	65	2.9	30	2.6
3.0 - 4.9	118	2.0	203	2.5	161	3.2	117	3.3
5.0 - 6.9	75	3.1	100	2.9	59	2.6	130	3.9
Type 3 accident rates (All states, without adjustment)								
0 - 0.9	128	1.4	110	2.7	13	2.0	31	4.3
1.0 - 2.9	178	1.4	163	2.1	96	2.9	53	2.6
3.0 - 4.9	125	1.9	223	2.5	170	2.9	139	3.4
5.0 - 6.9	75	3.1	100	2.9	59	2.6	130	3.9

Table 1.3 (Raff, 1953)

ACCIDENT RATES ON TANGENTS AND CURVES,[1] BY ROADWAY TYPE

	Two-lane roads		Three-lane roads		Four-lane roads: Undivided		Four-lane roads: Divided		Four-lane roads: Controlled access	
	Number	Per mil. vehicle miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles	Number	Per mil. vehicle-miles
Type 1 accident rates (All states, using adjustment factors)										
Tangents	6,474	3.7	227	8.1	1,348	6.4	982	4.6	774	2.2
Curves	1,794	3.3	39	10.2	210	6.5	177	3.8	380	2.9
Type 2 accident rates (Selected states, without adjustment)										
Tangents	4,259	3.1	115	5.3	757	3.3	829	2.9	774	1.7
Curves	1,355	2.6	1	2.5	86	1.9	86	1.3	380	2.0
Type 3 accident rates (All states, without adjustment)										
Tangents	6,474	2.3	227	2.5	1,348	2.7	982	2.9	774	1.7
Curves	1,794	2.3	39	2.8	210	2.2	177	2.1	380	2.0

[1]All volumes, grades, curvatures, etc.

Table 1.4 (Raff, 1953)

highways (Table 1.2) but the frequency of curves did not appear to have any consistent effect on the accident rate on two-lane curves (Table 1.3), even when the curves were subdivided by degree of curvature. The effect of frequency of curves on the accident rate on adjacent tangents was also inconclusive. The accident rates (Type 3) on tangents and aggregated curved sections were not much different (Table 1.4).

There was a large amount of irregularity in most of the results; few of the data can be fitted by smooth curves. The considerable scatter about the overall trends was attributed principally to the tremendous complexity of the problem itself and partly to inconsistency in the data (collected from 15 states).

1.4.2 Kipp Studies

The relationship between accident occurrence and certain roadway characteristics and roadside features was further investigated in a study carried out in Minnesota (Kipp, 1952). Minnesota was one of the 15 states included in the Interstate Highway-Accident Study by Raff (1953). The Kipp study considered two year's accident data (730 accidents of all types for 1948 and 1949) occurring on 420 miles of two-lane highways.

One aspect of the investigations dealt with accidents on tangent sections. The accident rate for shorter tangents was found to be lower but the difference was not significant enough to show conclusively that short tangent sections (interrupted by intersections and curves) were safer than longer tangent sections. Further analysis into accident rate at curves occurring at the end of these tangents indicated that a lower accident rate was associated with curves adjacent to tangents less than 3 miles in length (2.1 acc./million vehicles miles (MVM)) as compared to accident rates at at curves adjacent to tangents more than 3 miles in length (2.5 acc/MVM). Kipp (1952) attributed this difference to driver relaxation and inattention on long tangents. While not emphatically reflected in the accident rates for long tangents, it seemed to be reflected in the rate for curves that terminated these sections.

The study also showed (among many other findings) that:

(a) the accident rate for curves of 7 degrees or more was nearly four times the accident rate for curves of less than 3 degrees, and

(b) curves with restricted sight distances produced an average accident rate twice the rate for tangent sections with restricted sight distance (this average was also twice as great as that for curves with adequate sight distances).

Kipp (1951), in an earlier report on the same study, had also presented results of analysis for curved sections grouped by degree of curvature. The accident rates for these groupings were

Degree of curve	Rate (per MVM)
less than 3	1.37
3 to 5	2.48
5 and over	3.86

The accident rate for tangent sections was 1.14 compared to 1.54 accidents per MVM on curves.

The author concluded that "due to numerous factors the occurrence of motor-vehicle accidents cannot be predicted on the basis of roadway elements and roadside features . . . however, these various elements, along or in combination, make varying degrees of contribution to accident occurrence."

1.4.3 Baldwin Study

The 1954 AASHO document "A Policy on Geometric Design of Rural Highways" adopted the findings of the study by Baldwin (1946) as the basis for accident forcasting for rural highways. In this study, Baldwin related accident rates to such items as traffic volume, width of pavement, relative width of structures, roadway alignment, highway type and presence of intersections. Data were collected from 10 states, covering over 9000 accidents occurring on almost 4000 miles of major rural highways.

The findings were consistent with Raff's in that the accident rate increased as horizontal curves became sharper, and overall accident rates for tangent and horizontal curved sections were similar (Table 1.5). However, Baldwin's results indicated that for sharper curves (more than 3 degrees), the accident rate decreased as the frequency of curves increased. Put simply, it means that an isolated sharp curve in an otherwise good alignment is more hazardous than a series of similar curves together. In the same study, a similar situation was found with regard to restricted sight distance; the relatively infrequent restriction produced a higher incidence of accidents. This observed trend has led to the conclusion (AASHO, 1954) that "any highway feature which happens to be substantially below the standard of that generally prevalent on a given highway introduces a surprise element with resultant higher accident experience".

Highway or traffic element	Value or dimension		Accident rate, all reported accidents	
VOLUME (2-lane tangents)	*ADT*		*No. per million veh. miles*	
	Less than 3000		3.3	
	3000 – 5000		3.9	
	5000 – 8000		4.2	
	8000 – 9000		6.2	
	9000 and over		2.6	
PAVEMENT WIDTH (2-lane tangents)	*Feet*		*No. per million veh. miles*	
	Less than 18		5.2	
	18 – 20		3.8	
	20 – 23		3.5	
	23 and over		3.4	
STRUCTURE WIDTH (2-lane)	*Greater or less than approach width—feet*		*No. per 10 million vehicles per year*	
	− 1 or more		10.0	
	− 1 to + 5		5.8	
	+ 5 or more		1.2	
HORIZONTAL CURVATURE (2-lane)	*Degree*	*Curves per mile*	*No. per million veh. miles*	
	Less than 3	Less than 0.5	2.6	
		1 to 1.5	3.0	
		4 to 5	2.4	
	3 to 6	Less than 0.5	4.9	
		1 to 1.5	4.2	
		4 to 5	2.6	
	10 and over	Less than 0.5	13.2	
		1 to 1.5	5.9	
		4 to 5	3.5	
TYPE OF HIGHWAY	*Average for all volumes*		*No. per million veh. miles*	
	2-lane		3.7	
	3-lane		5.0	
	4-lane undivided		3.7	
	4-lane expressway		2.3	
INTER-SECTIONS AT GRADE	*Highway type*		*No. per 10 million vehicles per year*	
			Less than 10% cross traffic	10% or more cross traffic
	2-lane		3.7 – 1.8	10.0 – 6.0
	3-lane		7.2	42.5
	4-lane, undiv.		8.4 – 3.3	14.1 – 38.3
	4-lane, divided		5.1 – 5.2	17.4 – 27.4

NOTE: Accident rates for a specific State or region may differ materially from these composite values.

Table 1.5 (AASHO, 1954)

The 1954 AASHO document was revised in the mid-sixties to become the AASHO "A Policy on Geometric Design of Rural Highways : 1965". The section on safety was expanded to include a broader and more detailed treatment of the factors affecting highway safety. The effect of inconsistent design on driver surprise was recognized, and standardization of design was encouraged by which means "the driver becomes aware of what to expect on a certain type of highway".

The 1965 document also postulated that for two-lane rural roads, the safest alignments were straight and level roads without intersections and with insignificant numbers of private driveways. The study by Billion and Stohner, (1957) (See the following section) was quoted in support of this. However, to prevent drivers falling asleep while going along long tangents, "it is highly desirable to provide gentle curvature and avoid a fixed cross-section for long tangent sections".

Overall, the safety aspect in highway design had assumed greater importance, and the need to build safety features into roads was duly stressed.

1.4.4 Billion and Stohner Study

A study done in New York relating accidents to highway shoulders concluded that "alignment had more effect on accident experience than shoulder width"

(Billion and Stohner, 1957). A sample of 1753 fatal and severe injury accidents (from 1947 to 1953) were analysed with regard to shoulder width, pavement width and horizontal and vertical alignments. Accident experience was measured by an accident index, defined as the ratio of percent of accidents to percent of travel (an accident index > 1 implies a greater than average number of accidents occurred, and vice versa). The accident indices indicated that:

(a) narrow width shoulders (3-4 ft) had significantly higher accident frequency on poor alignments than wider shoulders, and

(b) regardless of shoulder width, grades > 5 percent, horizontal curves > 5 deg, and combination of grades and curves had 2.4, 6.3 and 9.5 times (respectively) the accident frequency of level tangents. Poor alignments, grades over 5 percent and/or curves over 5 degrees respectively, accounted for only 13 percent of travel but as much as 40 percent of the accidents.

In the study a "theoretical" accident distribution, where accident frequency was proportional to travel exposure (MVM), was compared with the observed accident distribution. The difference between observed and theoretical accident counts in each alignment and shoulder width category was tested (Chi-square statistic), and the results showed a significantly different (significance level not given) accident distribution (except for wide shoulders), the conclusion being that factors (e.g., alignment and shoulder width) other than travel exposure were influencing accident occurrence. The inclusion of the values of variance (for the calculation of confidence intervals) would have been very beneficial but the research method (relating geometric data to each accident) made such analysis difficult.

The 1965 AASHO document quoted this study in support of its conclusion that straight, level rural roads were the safest highway within their general class. However, caution was expressed regarding the reliability of the data; the sample sizes for some alignments were very small (especially for curve plus grade, and long-term trends in accident occurrence (8 years' data were used) were overlooked.

1.4.5 UK Studies

A number of studies (including Raff, 1953) that examined the effect of road curvature on road accidents were mentioned in "Research on Road Safety" (DSIR 1963). Results of before-and-after studies of improvements at bends showed that the number of accidents was substantially reduced at places where the curvature had been reduced or where other types of

Results of improvements at bends

Type of improvement	Reduction in injury-accidents (per cent)
Re-alignment of isolated bend (17 cases) . .	80*
Superelevation of isolated bend (6 cases) . .	60
Improved visibility at isolated bend (6 cases) . .	63
Major re-alignment of lengths of road (7 cases) .	95*

* Statistically significant at the 5 per cent level.

Table 1.6 (DSIR, 1963)

Effect of curvature on accident rates on rural roads in Buckinghamshire 1946–48 (*Two- and three-lane carriageways*)

Radius (ft)	Injury-accidents per million vehicle-miles (Numbers of accidents shown in brackets)	
Over 2900 (including straights) .	2·5	(177)
2900–1450	3·0	(48)
1450–950.	3·5	(21)
950–550	3·8	(9)
Less than 550	14·1	(18)

Table 1.7 (Charlesworth and Coburn, 1957)

Effect of curvature on accident rates on rural roads in Lancashire 1946–47

Radius (ft)	Injury-accidents per million vehicle-miles
Over 2000	1·5
2000–1000	2·5
1000–500.	4·0
500–200	3·7
Less than 200	16·7

Table 1.8 (Drake, 1949)

improvement had been made (Table 1.6). Studies of accident rates per vehicle-mile in Buckinghamshire (Charlesworth and Coburn, 1957) and in Lancashire (Drake, 1949) showed that there was a distinct tendency for accidents to cluster on bends, particularly on the very sharp curves (Tables 1.7 and 1.8). A British study that related accident rates at tangents and curves with average curvature (total horizontal curve deflection per unit length of section) was also included. The results of this study (Table 1.9) showed that:

Accident rates on straights, and on bends of different radii, on sections of 30-ft carriageway with different levels of average curvature, England, 1957–58

Non-junction injury accidents involving motor vehicles only

Average curvature (degrees per mile)	Accidents per million vehicle-miles (and numbers of accidents)				
	STRAIGHTS and bends of radius more than 5000 ft	BENDS			TOTAL
		radius 5000 ft–2000 ft	radius 2000 ft–1000 ft	radius less than 1000 ft	
0–40 . .	1·2 (284)	1·2 (33)	1·0 (4)	8·6 (18)	1·3 (339)
40–80 . .	0·9 (142)	0·9 (37)	0·9 (23)	1·5 (14)	0·9 (216)
80–120. .	0·7 (69)	0·5 (11)	0·9 (16)	1·6 (24)	0·8 (120)
Over 120 .	0·4 (15)	0·5 (3)	1·0 (19)	1·2 (19)	0·7 (56)
TOTAL .	1·0 (510)	0·9 (84)	1·0 (62)	1·8 (75)	1·0 (731)

Table 1.9 (DSIR, 1963)

(a) accidents tended to cluster at sharp bends, and

(b) accident rates were lower on "bendy" roads than on less "bendy" roads; this was especially true for straights, with low accident rates on roads where bends were frequent, and high accident rates on roads where curves were infrequent.

The above observations were reported to hold true for all injury and serious injury acidents, independent of the level of traffic flow, and to be applicable to both 30-ft carriageway and trunk roads in Britain. The second observation was in agreement with Baldwin's (1946) results for sharp curves (> 3 deg). However, Raff had reported an inconclusive finding between curves with different degrees of curvature.

The DSIR (1963) suggested on the basis of the above evidence, that:

(a) although a reduction in the curvature of a road would produce local reductions in accidents, the number of accidents over a greater length of road might well increase, presumably because of the higher speed attainable, and

(b) the policy of designing roads without excessively long straights was supported by the evidence.

It was however noted that the interpretations should not be regarded as conclusive.

1.4.6 <u>Kihlberg and Tharp Study</u>

The relationship of motor vehicle accidents to highway types and highway design elements was investigated by Kihlberg and Tharp (1968). The investigation was conducted in two phases; phase 1 studied accident rates (by type and severity) for various highway types, and phase 2 related these rates to various geometric elements of the highway.

During phase 1, data from California, Louisiana and Ohio were obtained and analysed. Accident and severity rates were calculated for homogeneous segments of known length and average daily traffic (ADT). In addition, the data were regressed using a model of the form

$$\log A = a + b_1 \log L + b_2 \log T$$

where A, L and T were the number of accidents, segment length and ADT, respectively. For phase 2, accident and geometric data for Ohio, Connecticut and Florida were related to homogeneous highway segments, each of known ADT and 0.3 mile length. For statistical analysis, the segments were arranged into 15 ADT groups, and the data within each group were regressed by using a model of the form

$$\log A = a + b_1 \log T + b_2 (\log T)^2$$

where A and T were the number of accidents per segment and the mean ADT, respectively. This analysis was done for each of the several highway types (classified according to the number of lanes, median, access control) subdivided by geometric elements (curve, grade, intersection, structure) for each accident type (multi-vehicle, one vehicle, injury, property damage, and all accidents). The results were presented as accident rates on "pure" segments (baseline rates) with multiplication coefficients for segments containing geometric elements or combinations of elements.

The results showed that:

(a) intersections (and access control) had the greatest effect on accident rates,

(b) having a combination of geometric elements increased the accident rate; a combination of elements gave an accident rate as high as six times the rate on a pure segment,

(c) partitioning of grade and curvature did not show any effect due to steepness of grade and sharpness of curve, and

(d) there was no evidence of accident severity being related to any geometric element.

An interesting outcome of phase 1 of the study was that accident rates were dependent on segment length; high accident rates were associated with short segments and low accident rates with long segments. Segment length was held constant for phase 2 of the study. Again, the results of the study could apply directly only to the individual states studied because the level of accident reporting varied from state to state. Overall, a study of this magnitude (with massive data input and regression calculations) is feasible only if the necessary data are readily available.

1.4.7 Dart and Mann Study

Further work on developing equations to predict accident potential was attempted by Dart and Mann (1970). They examined over 6000 accidents (for the years 1962-66) on 1000 miles (246 sections of varying lengths) of rural highway in Louisiana. Ten explanatory variables, including horizontal and vertical alignment, were used in a regression analysis to construct mathematical models to determine the contribution of the variables to accident occurrence (Table 1.10). The mathematical model relating the 10 variables to total accidents gave a coefficient of determination R^2 of 0.46. The 2 geometric variables appearing to have the greatest effect on accident rates were pavement cross-slope and the number of traffic

FOUR VARIABLES CONTRIBUTING MOST TO MULTIPLE R^2 VALUES

Accidents Analyzed	Variables	Variable Order	Multiple R^2
Total accidents: all first order variables versus main effects			
First order	TVR × CS	1	0.305
	TVR × TC	2	0.365
	LW × TC	3	0.386
	TVR × HA	4	0.398
	All		0.587
Main effects	TVR	1	0.241
	CS	2	0.265
	VA	3	0.272
	TC	4	0.278
	Ten		0.295
Fatalities versus injuries			
Fatalities	TVR × CS	1	0.136
	CS × TC	2	0.179
	HA × VA	3	0.199
	SW × CO	4	0.209
	All		0.424
Injuries	TVR × CS	1	0.304
	TVR × TC	2	0.358
	LW × TC	3	0.388
	TVR × HA	4	0.404
	All		0.610
Day versus night			
Day	TVR × CS	1	0.307
	TVR × TC	2	0.354
	T × TVR	3	0.374
	TVR × HA	4	0.384
	All		0.588
Night	$(TVR)^2$	1	0.258
	TVR × TC	2	0.300
	TVR × CS	3	0.327
	LW × TC	4	0.347
	All		0.537
Dry versus wet road			
Dry	$(TVR)^2$	1	0.303
	TVR × TC	2	0.352
	TVR × CS	3	0.378
	TVR	4	0.402
	All		0.615
Wet	TVR × CS	1	0.291
	T × TVR	2	0.331
	$(T)^2$	3	0.337
	TVR	4	0.352
	All		0.487

Note: CS cross slope; CO continuous obstructions; TC traffic conflicts; HA horizontal alignment; T trucks; TVR traffic volume ratio; LW lane width; SW shoulder width; VA vertical alignment

Table 1.10 (Dart and Mann, 1970)

conflicts (number of traffic access points) per mile. Horizontal alignment, expressed as the percentage of the length of a highway section that had a horizontal highway curvature in excess of 3 degrees, was found to be related to accident occurrence, but the effect was not clear.

Although a broad range of geometric variables was studied, only 46 percent of the variation was explained. This pointed to the complexities involved in formulating a mathematical model for accident prediction and showed that geometric variables alone are not sufficient to describe accident causation. The application of the findings was also limited to the area where the data were obtained (i.e. Louisiana), since no cross-validation was attempted.

1.4.8 Australian Studies

An analysis of fatal accidents on rural State Highways in New South Wales for three years (1966-68) was carried out by Cowl and Fairlie (1970). A sample of 750 fatal acccidents were classified by location of accident, time of day, types of vehicle involved, age of drivers, accident type and road alignment. The results showed that

(a) 50 percent of all fatal accidents were associated with curved alignment,

(b) 40 percent of all fatal accidents occurred at curves with radii less than 1500 ft,

(c) 67 percent of all fatal accidents on or adjacent to curves occurred where the curve radius was 1000 ft or less,

(d) 30 percent of all fatal accidents were "head-on collision", and

(e) 20 percent of all fatal accidents were "ran off road" accidents

(f) head-on-collision and ran-off-road accidents were the most common types of fatal accidents; together they constituted 65 percent of all fatal accidents occurring on curves with radii less than 600 ft.

The results indicated that fatal accidents were highly associated with curved alignment. However, in the absence of exposure data, the study could provide only a qualitative insight into the extent of the safety problem, and this information is useful only at a first level of analysis (e.g., identifying the most common type of accidents on curved alignments).

1.4.9 Wright and Robertson Studies

The traditional approach has usually involved making inventories of geometric and traffic variables and relating them to accident statistics; included in the data base are data for sites at which no accidents may have occurred. Some recent studies have departed from the traditional research method, and have focussed on accident locations. The recent trend is towards in-depth investigation of accident sites.

A study that involved in-depth investigation of crash and comparison locations in Georgia was reported by Wright and Robertson (1976). Crash locations were single-vehicle, fixed-object, fatal accident sites, and comparison locations were roadway sections 1.6 km upstream of the accident sites. At each location, profiles of curvature, superelevation and gradient, as well as inventories of fixed roadside objects, were collected over a 0.32 km length of roadway; other factors recorded were type of road, number of lanes, lane width and shoulder width. A sample of 300 crash-comparison pairs (located in a variety of roadway types, topography and land usage) was analysed. The results were presented as a comparative analysis of roadway characteristics at crash locations against those at the comparison locations.

The most significant finding was the large difference in road curvature between crash and comparison locations. Crash locations were more often curved (81 percent had curves) and with more sharp curves (50 percent had curves > 6 degree) than comparison locations (55 percent and 24 percent respectively). The difference in the accident distributions (Table 1.11) was statistically significant ($p < 0.001$), and curvature in the comparison group was distributed similarly to the 25 percent sample of all roads in Georgia. At crash locations sharp curves were most prevalent from 107 m upstream to 15 m downstream from the crash site (referenced to the object that was hit) and more sites (69 percent) were on the outside of curves than the inside. The results for superelevation closely paralleled those for curvature; steeper cross-slopes are generally associated with sharper curves. Downhill gradient was more frequently a characteristic of the approaches to crash sites, which were often near points where downhill gradient ended and uphill gradient began. Consideration of maximum road curvature and minimum gradient simultaneously resulted in substantial discrimination between crash and comparison locations; the combination of maximum curvature (> 6 deg) and minimum gradient (< -2 percent) was 4 times more prevalent at crash locations (26 percent vs 6 percent).

Maximum Curvature (degree)	**Crash**	**Comparison**
0	19	45
.0001-1	1	2
1.001-2	3	4
2.001-3	4	7
3.001-4	9.5	8
4.001-5	6	5
5.001-6	7.5	6
> 6	50	24

Table 1.11 **Proportion (%) of Crash and Commparison Sites with the Maximum Curvature up to 152 Metres from Fatal Fixed Objected Crash and Comparison Sites (Extracted from Figure 3, Wright and Robertson, 1976)**

By comparing crash occurrences against the functional classification of the roads, it was shown that the majority (83 percent) of crashes occurred on non-local roads, which constituted only one third of all roads. A survey of fixed objects showed little difference in potential hazard near the roadside (i.e. similar frequency of fixed objects at crash and comparison locations). About 90 percent of objects struck were within 11 m from the pavement edge.

The study showed that:

(a) the highway segment most prone to single-vehicle, fixed-object, fatal crashes could be identified from its geometric features (curvature and gradient) and its functional classification,

(b) roadside obstacles influenced the severity of run-off-road (ROR) crashes.

An extension to the study on roadside hazard modification by Wright and Robertson (1976) was carried out by the same authors (Wright and Robertson, 1979). The research method used was identical but the crashes studied covered fatal, personal-injury and property-damage-only single vehicle fixed-object accidents (i.e. all levels of severity). A sample of 300 crash locations closely resembling the statewide fixed object crash population was drawn from 3 counties in North Georgia. The study area included a variety of land uses, roadway type and topography.

Maximum Curvature (degree)	Crash	Comparison
0	16	28
.0001-1	2.5	1.5
1.001-2	4	8
2.001-3	5	7.5
3.001-4	2.5	8
4.001-5	5	7
5.001-6	5	2
> 6	60	38

Table 1.12 Proportion (%) of Crash and Commparison Sites with the Maximum Curvature up to 152 Metres from Crash and Comparison Sites (Extracted from Figure 2, Wright and Robertson, 1979)

The findings were similar to the earlier study. Road curvature was the most prominent feature in comparing roadway characteristics between crash and comparison locations. Crash locations had more curvature, with more sharp curves, and the difference in the accident distributions (Table 1.12) was statistically significant ($p < .001$). In fact, 48.7% of the crash locations had curves > 9 degrees in the vicinity of the accident location compared to 27.1% at the comparison locations. At crash locations, sharp curves (> 6 degrees) were most prevalent from 107 m upstream to 15 m downstream of crash site, with maximum mean curvature at a point 15 m upstream of the crash site. Other findings included;

(a) more crashes on the outside of curves,

(b) downhill gradient more common upstream of crash sites than comparison sites,

(c) combination of maximum curvature and minimum gradient resulted in substantial discrimination of crash and comparison locations,

(d) roadways at crash locations had significantly narrower pavements and shoulders,

(e) non-local roads were over-represented in fixed object crashes,

(f) potential roadside hazard differed little between crash and comparison locations, and

(g) about 90 percent of the objects taking the brunt of impacts were within 9.1 m of the pavement edge.

The results of this study generally confirmed the findings of the earlier one. The combined results suggested a clear set of priorities for removing roadside hazards, or modifying them or the roadway. In particular, the two geometric features, curvature and gradient, in conjunction with the functional classification of roadways, could be applied to identify highway segments prone to fixed-object crashes. The study also showed that higher standard highways (slight curve, flat grade, wide pavement, wide shoulder) are less hazardous with respect to fixed object crashes.

1.4.10 Dunlap et al. Study

The accident data analysis in the study by Dunlap et al (1978) indicated some surprising results. Dunlap et al reviewed 9822 accidents during 2.5 years (1966-1968) on the Pennsylvania Turnpike, and 553 accidents during 4.5 years (1966-1979) on the Ohio

Turnpike. Geometric (grade and horizontal curvature), traffic and accident data were analysed to determine the extent to which horizontal and vertical alignment, both singly and in combination, influenced the accident rates. The analytical technique used was a dummy variable multiple regression technique on stratified levels of vertical alignment (highway grade) and horizontal alignment (horizontal curve).

The results generally showed no evidence of effects that could be attributed to grades and curves in combination. The Pennsylvania Turnpike accident rate was not dependent on grade, but did increase with increasing curvature. The Ohio Turnpike showed no significant accident dependence on either grade or curvature, except that a specific 1 degree curve on a 3 percent downgrade had a very high accident rate. This accident history appeared to be highly associated with pavement wetness , and to be associated to some extent with worn tires. All 1 degree curves in Ohio had a high incidence of wet-pavement accidents. Curves around 1 degree in Pennsylvania also had a somewhat higher incidence of wet-pavements accidents than did curves of other degrees of curvature.

Analysis of Ohio Turnpike accident data showed no significant accident association with horizontal curvature. This could be due to:

(a) the disturbing effect from the high incidence of wet weather accidents for curves of 1 degree, and

(b) the narrow range of curvature in the data (the Ohio Turnpike had a maximum curvature of 2.5 degree).

1.4.11 Wright and Zador Study

The research method employed by Wright and Robertson (1976) to study fixed object crashes in Georgia was adopted by Wright and Zador (1981) to identify roadway characteristics where single-vehicle, fatal, rollover crashes occurred, and to develop guidelines for the reduction and/or elimination of such crashes. Data on geometric features and roadside obstacles were collected at 214 fatal rollover accident locations and at an equal number of comparison locations, which were chosen to be roadway sections 1.6 km upstream of the crash sites (the position at the roadway edge adjacent to the point at which rollover commenced).

The most prominent roadway feature in the comparative analysis was horizontal curvature, particularly along left curves. Crash locations had more curvature and more sharp curves. Sharp curves were prevalent near or upstream of crash sites, with maximum curvature occurring on average 46 m upstream from crash sites. Steep downhill gradients were also found to be strongly and significantly associated with rollover crash locations. The pattern of distribution of longitudinal slopes observed in earlier fixed object crashes, in which negative slopes tended to occur upstream and positive slopes downstream was also apparent at rollover crash locations.

The authors contended that differences in rollover crash rate were explicable in part by the design features of the roadway, the configuration of the roadway surfaces, and the type and density of roadside obstacles. Undesirable geometric design features, especially excessive left-turning curves and downslopes, could increase the demands on the driver-vehicle system and contribute to the loss of vehicle control and possible encroachment on to the roadside.

1.4.12 Hall and Zador Study

A companion study surveying single vehicle, fatal, rollover crash sites in New Mexico was carried out by Hall and Zador (1981). The research method was again identical to that of Wright and Robertson (1976) A sample of 151 fatal rollover crashes in New Mexico was investigated.

Horizontal curvature was the most significant feature. The average curvature at crash locations was significantly higher than at the comparison sites.

This was especially prominent in the area that was most critical to the approaching driver i.e. the area from 137 m upstream to 15 m downstream from the crash site. Left-hand curves were over-represented at crash sites, and the downgrade at the crash sites was significantly steeper than at comparison sites. Curvature and gradient data showed that roadway geometrics were significantly worse at the locations of fatal overturning crashes than at the comparison locations. There was little difference in the number of spot fixed objects (e.g. trees, poles); the front slope and the depth of embankment or ditch were significantly greater at crash locations than comparison locations.

The New Mexico crash sites were characterised by sharper curvature and curves to the left, steeper downgrades and embankments, and greater embankment depths than the nearby comparison sites. The Georgia sites exhibited significantly sharper curvature, flatter grades, more spot fixed objects, and steeper but shallower embankments than the New Mexico sites. Six conditions of combined horizontal and vertical alignment were used to compare the data from Georgia and New Mexico. Chi-square testing showed that the condition classification was dependent on the state. The difference in the values of alignment characteristics between the two states suggested that priority schemes for selecting hazardous locations cannot rely on uniform nationwide criteria, as each state has different alignment characteristics.

1.4.13 McBean Study

A recent British study (McBean, 1982) examined the influence of road geometry at a sample of accident sites selected within a 20 km radius of the Transport and Road Research Laboratory. The study was based on the approach taken by Wright and Robertson (1976). Data for more than a dozen physical features, including curvature, gradient and sight distances, were collected from nearly 200 single and multi-vehicle non-junction accident sites and from an equal number of control sites. Most of the sites were on lightly-trafficked rural roads. Each physical feature was represented as taking one of a number of levels (e.g. 4 levels for radius of curvature : > 3000 ft, 1500 to 3000 ft, 500 to 1500 ft and < 500 ft). The matched pair was characterized under each feature by a two-dimensional (accident vs control) matrix, and McNemar's test was applied to determine the relative probabilities (to a base level) of accident sites and control sites being associated with a given level.

The results suggested that curves down to a radius of about 1500 ft (about 460 m) did not produce marked safety problems. Short sight distance (below about 200 m) was found to be associated with higher accident risk through their association with bends. There was insufficient data on gradients to allow a "sensitive" test. No clear relationship was detected between accident risk and the other features studied.

The study supports the finding of earlier studies that horizontal curvature is strongly related to accident risk. One of the weaknesses of the study was that the interacting effect among different features was not controlled. Furthermore, the findings were restricted to relatively lightly-trafficked roads.

1.4.14 Neuman et al. Study

The influence of roadway geometrics on accident experience at isolated horizontal curves on two-lane rural highways was studied by Neuman, Glennon and Saag (1983), using a data base assembled from the geometry files of four states (Illinois, Florida, Ohio and Texas), and accident records for a 3-year period. Pure curve-and-tangent segments, each 1 km long and with uniform cross-section geometry throughout, were identified. Each segment comprised a curve flanked by tangents of 0.12 mile minimum length; there were 3304 segments altogether. Two separate analyses were undertaken; analysis of covariance was used to study the separate effects of five basic geometric and traffic variables (ADT, degree of curve, length of curve, roadway width, shoulder width), and discriminant analysis was applied to a detailed study of the geometric and environmental characteristics of sites with high and low accident rates.

The analysis of covariance suggested that only the degree of curve had a sizable influence on accident rate. The discriminant analysis indicated that hazardous roadside design was the largest contributor to accident experience at highway curves; the other variables (in order of decreasing discriminating power) were shoulder width, length of curve, degree of curve and pavement rating. Roadside hazard was measured by roadside rating factors; the roadside hazard was described by (a) roadside slope break, (b) clear-zone width, (c) obstacle coverage factor, and (d) severity indices for roadside slope and obstacles. Pavement rating factors were related to surface roughness and texture.

1.4.15 <u>Discussion</u>

The descriptive (comparative) studies indicated that there seems to be strong association of sharp curvature with high accident occurrence (an association is not the same as a cause-effect relationship). However this association is weaker in studies involving mathematical equations that included a number of other explanatory variables (Kihlberg and Tharp, 1968; Dart and Mann, 1970; Dunlap et al, 1978; Neuman et al, 1983), which suggests that curvature on its own has only a modest effect on the level of accident occurrence. The apparently strong association in the descriptive studies could be attributed to the fact that sharp curves are usually indicative of a lower standard in the overall alignment design and the strength of the association could be due to a combination of design elements. (The philosophy of curve design is to ensure coordination of geometric elements, hence the covariation of explanatory variables). All the reviewed studies indicated a strong and positive relationship between accident occurrence and a combination of low standard design elements (for example sharp curves at steep grades). Hence it is clear that low design standard is correlated with low safety, while the true individual effect of horizontal curvature on safety is still uncertain.

Studies by Kipp (1952), Baldwin (1946) and DSIR (1963) indicated that accident rates at curves tended to be lower as the frequency of curves (or average curvature) per unit length of road increased. This finding is equivalent to an isolated curve being more hazardous than one within a series of curves. This implies that consistency in the road alignment is an important consideration.

The method used in the studies can be grouped under two categories.

(a) Mass data analysis;

(b) Engineering investigation of accident sites.

Mass accident analysis typically involved taking mass inventories of geometric (and traffic) variables and relating them to accident statistics. The analysis was either descriptive (comparative) or predictive with the latter usually involving regression analysis. Mass data analysis has been the classical technique used by researchers to study the accident-geometry relationship. The popularity of this approach has no doubt been mainly due to the availability of data bases containing accident statistics and road geometry data. The deficiencies in the existing accident data bases have been pointed out in section 1.5, the major ones being a varying reporting threshold and biases in the data. The major deficiency in the road geometry data base is that the data base has been collected mainly for management purpose and the geometry data in its original form are generally not suitable for direct input into safety-related analysis. The geometry data are often quite old and have not been updated and frequently do not contain sufficient details. A major task in mass accident analysis is to assemble a data set that links accident and geometry data, and this often requires a matching procedure to reconcile accidents locations with the reference system used in locating geometric elements or vice versa. The outcome of the analysis is therefore dependent on the reliability of the accident data set and the geometry data set as well as the goodness of the link between the two data sets. It has been pointed out earlier that it is as yet uncertain to what degree horizontal curvature is related to accident occurrence. It is suggested that there is scope to improve on the results of mass data analysis through better control in the input data (e.g. better accident reporting procedures and up-to-date and detailed inventories of geometric elements).

The engineering investigation of accident sites involved taking inventories of geometric and other road elements at accident sites and control sites (the control sites were in the vicinity upstream of the accident sites). This approach practically eliminated most of the major deficiencies associated with the input data for the mass accident analysis (except the accident reporting threshold), as well as not having to control for the ADT variable. However, the method is resource-intensive and the resultant smaller sample size implies that there will be numerical instability (or lack of significance) if too many variables are controlled during the analysis. Though the approach is methodologically superior, it is not economically practical to be used on a large scale.

An attempt was made during the initial stage of this project to assemble a road geometry data set for linking with accident statistics for the New Zealand state highways. This required extracting data from Highway Information Sheets (published and presumably updated annually) and aerial photographs (around 10 years old). The aerial photographs (scale of 1:4000) are used for determining the length and angle of deviation of curved sections. A pilot study revealed that this exercise would be extremely labour intensive and the resultant data set would not produce particularly reliable results. Recent development of data acquisition systems such as the ARRB road geometry data acquisition system (RGDAS) (Rawlinson, 1986) would be very useful in collecting up-to-date inventories of road geometry data. The RGDAS can measure and record (while travelling at highway speed) such data as distance, gradient, horizontal curvature, crossfall, superelevation, vertical curvature, and vehicle speed. It is expected that the application of such microprocessor-based data acquisition system would help to improve the reliability of the input data.

Apart from the difficulties involved in assembling the input data and interpreting the results of the studies by mass analysis or engineering investigations, the study techniques are generally not capable of determining why the accidents happened or where the driver-vehicle lost control. The study techniques are only able to establish an association between the accident and geometric attributes. Correction work on the geometric elements in an attempt to improve safety is based mainly on this association. If the correction work resulted in a reduction of accident occurrence, there is no certainty that the reduction was caused by the correction work. In view of the limitations of the study techniques as described in the various reviewed studies, it seems beneficial that the road and traffic engineers approach the safety problem from a different perspective.

1.5 HUMAN FACTORS IN ROAD SAFETY

The preceding section (Sec. 1.4) has shown that statistical analysis of accident data can successfully produce some form of correlation between the variables involved (e.g. accident rate vs horizontal curvature). This provides some indication of which accident remedial works should be given priority (e.g. improving the standard of horizontal alignment). However, such mass data analyses are not capable of identifying the underlying causes of accident involvement.

In-depth accident investigation and accident reconstruction involving a multi-disciplinary team has brought a better understanding of the factors involved in accident causation. Such studies have shown that human factors, alone or in combination with other factors, account for around 95% of identifiable causes of accidents (Shinar, 1978). This implies that an understanding of the human factor in the driving task should be an important area of road safety research.

An overview of the different approaches to the study of driver behaviour and accidents is provided by McKenna (1982), who examined and discussed several classes of studies.

(a) Accident proneness studies are done to distinguish characteristics such as personality traits, that are associated with accident involvement. The major conceptual difficulty is the confusion of how accident proneness should be defined, and even if successful, accident proneness could not provide psychological antecedents of accident involvement i.e. what were the psychological factors operating immediately prior to the accident occurring.

(b) Differential accident involvement studies involve attempts to predict or discriminate, on the basis of psychological tests (e.g. embedded figure test), accident involvement or non-involvement. The major attraction of this approach is that, if successful, it could provide a theoretical understanding of human error associated with accident involvement.

(c) Studies that attempt to relate accident involvement with temporary physiological changes, such as effect of alcohol and drugs and fatigue. The major difficulty with this approach is in assessing exactly how large the effect is.

(d) Traffic conflict studies where the degree of accident involvement is correlated with traffic conflicts, the latter being defined in terms of evasive actions (e.g. braking). The sought-after relationship has to date not been entirely satisfactory and, even if successful, could not explain the psychological antecedents of accident involvement.

(e) Studies relating road accidents with biorhythm theory, in which human behaviour and emotions are assumed to vary from day to day through an interaction of three cycles. The major criticism of this method is the lack of hard evidence of the existence of the rhythms.

(f) The statistical approach, in which accident statistics are related to various factors such as geometrics, drivers, vehicles and the environment. This approach is very useful at a first level of analysis (eg. assessing the seriousness of the accident problem). Engineers have almost invariably relied upon this approach in identifying 'blackspot' in a road network, e.g. the studies by Raff (1953), Cowl & Fairlie (1970).

(g) Driver improvement schemes involving changing the road users. The main problem with this approach is the lack of a good understanding of the requirements of the driving task (i.e. what abilities are required for error-free driving).

(h) Modifying the environment which are considered accident black spots. The chief problem with this approach is that there are an infinite number of modifications to the environment which can be made for effective prevention of future accident involvement. The current approach to modifying the environment is to hypothesize the nature of the human error and then make appropriate modifications. Hence modification of the environment still requires an understanding of the human factor involved in the driving task.

The many different approaches to the study of accident involvement have been less than successful because most of these approaches apparently have been carried out independently of the others. This state of affairs could be attributed to the fact that accident involvement is really a result of failure in one or more components of the driver-vehicle-environment system. This implies the study of accident involvement is necessarily a complex one and requires an interdependent study of the various components of the system, (eg. by treating the various approaches listed above as complementary and establishing links between them).

In most of the studies dealing with human factors, the emphasis is on accident-related behaviour or characteristics. The framework of human factor research is thus focussed mainly on accident involvement in the quest to find the causes of accidents. Viewed from this perspective, the majority of human factor studies are geared towards the safety aspect of road transportation. Having road safety as the prime driving force in human factor research is not necessarily undesirable. However, it does make the field of human factors research rather restricted. As Johnston et al (1980) has pointed out, the primary purpose of transportation is mobility, with objectives such as safety, accessibility, energy conservation and minimal adverse social and environmental impacts being among the sub-goals. Therefore it does not follow that the most efficient approach is to base our knowledge almost solely on accident-related behaviour. Johnston et al recommends a shift in emphasis away from accident-related behaviour to the study of normal, on-road behaviour. Examples of non-accident-related studies are overtaking behaviour (Troutbeck, 1981) and speed behaviour on rural curves (McLean, 1978). In the latter study, the findings have provided the impetus for a change in the concept of design speed for horizontal curve design (NAASRA, 1980).

A noticeable shift in the study of driver behaviour in recent years is the emphasis on viewing the driving task as more than simply a task-related activity; it is also influenced by non-task-related personal factors (Naatanen and Summala 1976, Shinar 1978). The earlier driver behaviour models typically represent the driving task as a skilled performance and thereby assume that task analysis would provide the essential information necessary for the safe and efficient operation of the transportation system (Forbes, 1972). Research tends to focus on sensory threshold, perceptual abilities and motor dynamics. This task-demand model is generally valid in a force-paced driving environment (such as peak-hour city driving) and also provides a good framework for the study and design of the man-machine interface. However, it is generally recognized that most driving, and particularly so in rural areas, is self-paced. In self-paced driving, the whole exercise is under the control of the driver, which allows the driver to adjust the level of task demand to suit the driver. Under this situation, there exists plenty of scope for non-task-related personal factors to interplay with the driving task. Naatanen and Summala (1976) have strongly argued that motivations are major determinants of driver behaviour. They further argued that driver behaviour is determined by a balance between these motivational factors ('extra motives') and both the driver's perception of risk and his willingness to tolerate it; the level of risk tolerance is dependent upon the nature and strength of the motivational forces present at the time. A frequently used example to illustrate the importance of extra motives in driver behaviour involved a series of experiments in Sweden, where it was shown that sign detection under normal driving condition varied between 20 and 80 percent, the success rate apparently being dependent upon the subjective importance of the sign to the drivers (Naatanen and Summala, 1976).

An aspect of human behaviour that has generated considerable attention in various fields of accident analysis and prevention involves the variations of user's subjective risk (perceived risk) in response to changes in the system. Among the practitioners of safety, this amounts to how the effectiveness of a safety project is eroded or enhanced by changes in the maintenance of user's subjective risk. In terms of road safety, the concern is whether (and by how much) drivers modify their behaviour in response to changes in the traffic system, such that the overall effect results in greater or less than the expected improvement in safety.

Evans (1985) related the actual safety change in the traffic system to the expected change in the traffic system by introducing a "human behaviour feedback parameter", f, to a model of the form:

(actual effect) = (1 + f) (engineering effect)

The engineering effect (or the expected change) is derived from straight forward engineering calculation based on a non-interacting model (i.e. the change in one component of the system does not affect the other components). Evans reviewed 26 cases of published research and showed that the value of f can be either positive, negative or zero. For safety-related changes in the traffic system, the different values of f correspond to the following situations.

(1) $f > 0$: safety increased even more than expected.

(2) $f = 0$: safety increased as expected (non-interacting model).

(3) $-1<f<0$: safety increased but less than expected (risk compensation).

(4) $f = -1$: no safety increase (risk homeostasis).

(5) $f < -1$: change led to safety decrease (perverse compensation).

A special case of Evan's model with the parameter $f = -1$ (i.e. no safety increase or risk homeostasis), has been the subject of many debates in recent years (Wilde, 1988; McKenna, 1988). Risk homeostasis theory (RHT) as proposed by Wilde (1982) is based on the hypothesis that road users tend to maintain a certain target level of risk irrespective of the external conditions under which their task is performed. This target level of risk is assumed to be directly under the control of the road users. RHT implies that any safety measures would be ineffective unless it involves motivational intervention to lower the users' preferred level of accident risk. The theory has been judged plausible but untestable, since target levels of risk are unmeasurable, and no all embracing index of accident loss exists (Adams, 1988). There has not been any concensus to date, regarding the validity of RHT and it appears that it will be the subject of further debate in the future.

1.6 DRIVER BEHAVIOUR RESEARCH

Driver behaviour research is defined as research directed at describing, classifying, understanding and predicting the behaviour of the driver in the operation of the road transport system (Johnston and Perry, 1980). A major aspect of driver behaviour research is therefore to study the normal driving behaviour of drivers on the road. There is relatively little research on normal driver behaviour, which is partly because of the traditional emphasis on accident-related behaviour. There is however also major difficulty in establishing measurements that are appropriate for developing a comprehensive driver behaviour framework. The choice of measurement at the present stage of driver behaviour research is very much dependent on the immediate objective of the research. For example, measurement for research into sign-design are typically conspicuity, legibility and comprehensibility. It is fair to say that research of normal driver behaviour at the present time is primarily still at the stage of merely describing and classifying driver behaviour, while contributing towards the long term goal of being able to understand and predict the behaviour of the driver on the road.

It is emphasized here that the study of normal driver behaviour from the perspective of the road and traffic engineer, which is also the approach taken in this project, is generally concerned with the on-the-road performance of the driver-vehicle system in relation to the road geometrics. 'Measurement' of driver behaviour is thus expressed in terms of performance indices of the driver-vehicle system within the road environment. Commonly used performance indices are speed and derivatives of speed (such as forward acceleration), and directional control (such as lateral placement, wheel path trajectory and encroachment pattern). In situations involving interaction with other vehicles, some frequently used performance indices are the headway between successive cars, the lateral clearance to opposing vehicles, and headways and lateral clearance during overtaking manoeuvres. For the case of curve negotiation, the lateral acceleration and the side friction requirement are also useful performance indices.

The performance data gathered through unobtrusive field observations are indicative of the manner in which the driver-vehicle entities 'use' the road, and this information is useful to the road and traffic engineer. The performance data are however generally not capable of providing the reasons for driver behaviour (i.e. they cannot explain why drivers choose to perform in a particular manner).

1.7 DRIVER BEHAVIOUR AT HORIZONTAL CURVES

Past research on driver behaviour at horizontal curves is reviewed from an engineering perspective. The studies reviewed are those concerned with unobtrusive observation of drivers. Studies that involved instrumented vehicles and/or volunteer drivers are also briefly discussed.

1.7.1 Taragin Study

One of the earliest studies of driver behaviour at horizontal curves is that by Taragin (1954). The study involved measuring spot speeds at 35 horizontal curves (gradient < 3 %) on 2-lane rural highways. The curves had minimum sight distances (SD) ranging from 200-655 ft (60-200 m) and curvatures of 3-29 degrees (radii of 580-60 m). The minimum SD was not linearly correlated with curvature even though there was a tendency for flatter curves to have larger minimum SD's. Speed profiles were determined from speeds obtained at 100 ft intervals extending 500 ft each way from the curve mid-point, for 15 curves in New York; speed at the point of minimum sight distance was measured for 20 curves in Maryland, Illinois, Minnesota and South Carolina. (The sight distance was based on an eye height of 4.5 ft and object height of 4 inches). There was a sample size of around 125 free-moving vehicles (not meeting opposing vehicle and at least 6 s headway from the vehicle ahead) for each direction of travel at each curve, resulting in a total sample of 8400 passenger vehicles for the 35 curves. The speeds were apparently measured in dry and daylight conditions.

The speed profiles at the 15 locations in New York showed that "drivers of free-moving vehicles do not change their speed appreciably after entering a horizontal curve", and "any adjustment in speed that is made because of curvature or sight distance is made on the approach to the curve".

The total sample of 8400 speed values at the points of minimum SD for all 35 curves showed that:

(a) speed on the inside lane was about the same as on the outside lane, even though the minimum sight distance on the outside lane was about 20% greater;

(b) superelevation seemed to have no effect on the operating speed;

(c) the sideway force coefficient (f), as computed using the curve centre-line radius, showed that f increased as the degree of curvature increased (or radius decreased); f values were also slightly lower for the outside lane; for curves > 15 degrees (radius < 116 m) about 10% of drivers had f > 0.3, while for curves < 6 degrees (radius > 290 m) most drivers had f < 0.16;

(d) for a given minimum SD, vehicle speeds were higher on the inside lane; for SD > 400 ft (112 m), few drivers exceeded the safe stopping sight distance;

(e) operating speed is linearly related to the degree of curvature; speeds exceeding the design speed tend to occur on curves > 6 degrees (radius < 291 m); curvature had 3 times more of an effect on operating speed than did the minimum SD; the best-fit equation relating average speed V (in mph) and curvature D (in degrees) was

$$V = 46.26 - 0.746D \ (r^2 = 0.67)$$

The results of Taragin's study have been much-quoted in many later studies. It should be pointed out that information was lacking on both the curve length and curve transitioning. Traffic flow conditions were also not made available, but it may be assumed that traffic flow was light enough for free-moving vehicles to be selected. The accuracy and method of speed measurement was not mentioned. There was also no indication of the degree of corner-cutting, which is quite likely at some of the curves. The approach speed in the vicinity of the curve entry point was measured but was not used in determining the extent of speed adjustment on the approach.

It was noted that speeds at the points of minimum SD, which were typically about 100 ft ahead of the curve mid-points were used for analysis but as there was little change in the speed profile within the curve, these speeds could just as well have been the speeds at the curve mid-points. It is also not clear if the curvature used was measured at the point of minimum sight distance. If the curves were simple untransitioned curves, as indicated by Good (1978), the radius would have been a constant value within each curve and the point of measurement would not have been important, and Taragin's speed-curvature relationship could also be applied to the mid-points of the curves.

1.7.2 <u>Tharp and Harr Study</u>

A detailed study of vehicle speeds on various geometric features was carried out by Tharp and Harr (1965), to evaluate a mechanistic model for rating geometric features which included 3 horizontal curves with radii of 42, 1091 and 1273 ft (13 m, 332 m, 410 m respectively). The speed along each curve approach and in the vicinity of curve entry was obtained by photographing vehicle movement through graduated road sections (at 50 ft interval) using a 16 mm motion camera positioned at a vantage point and at right angles to the vehicle line of motion; speed was estimated from the times of travel across the graduated sections.

The mean speed profile for the flattest curve (radius 1273 ft, length 1500 ft, no superelevation, zero gradient, no pavement widening) showed the mean speed decreasing steadily from 600 ft before curve entry up to 400 ft into the curve; minimal speed adjustment was observed over the next 200 feet.

The mean speed profiles for the outside lane of the second curve (radius 1091 ft, length not given, some superelevation, pavement widening on the inside lane) showed reduction in the mean speed from 700 ft before curve entry and continuing for 200 ft into the curve; a strong acceleration was apparent over the following 200 ft for passenger cars (but not for trucks). The effect of opposing vehicles on the inside lane seemed not to have influenced the general trend in the mean speed profile.

The mean speed profile for the sharp curve (radius 42 ft, considerable superelevation, probably short length since it was a 90-degree bend) showed that approaching vehicles began to reduce speed approximately 1000 ft prior to the bend. However, in this case vehicles continued their deceleration at a progressing increasing rate as the feature was approached. When the minimum speed was reached (at approximately the centre of the curve, the vehicles immediately undertook an acceleration.

It was noted that the sample sizes used were generally small (< 100), and the 3 curves were all quite different in their design characteristics. However, the mean speed profiles indicated varying mean speed within the curve and it seemed that speed adjustment commenced further upstream from the curve, and at a higher rate of reduction as the curve radius reduced.

1.7.3 Emmerson Studies

Emmerson (1969) reported the results of speed tests on cars at six sites on horizontal curves along two-lane roads in rural areas of Cheshire and Lancashire. The sites were chosen in such a way that the only factor likely to affect speed was the road curvature. The six sites were all isolated curves with minimal sight distance restriction (>400 ft) and road gradients of 3 percent or less. The radius of curvature ranged from 70 - 1150 ft (21 - 350 m). The speed of cars at the centre of the curve was measured (by a concealed speedmeter) in a dry and good visibility environment and when traffic flow was less than 400 vehicles/hour. Except for one site, measurement was for one direction only, either the inside or the outside, depending on the ease of concealing the speedmeter. Only vehicles that did not use a corner-cutting strategy (10% did) and with a minimum of 7 s headway to the preceding vehicle were selected, resulting in a total sample of 650 cars for all the 6 sites. The distribution of the speeds on the straights was also measured at locations well in advance of the curve (about 80 observations at each site).

The results showed that:

(a) corner-cutting was more prominent on curves less than 500 ft (152 m); it was found SEE ERRATA that many cars had shifts of 2 to 3 ft in lateral placement between the beginning of the curve and its centre;

(b) the speed distributions showed that for the curves with a radius of 900 - 1150 ft, there was little change in the speed distribution compared with that along the straight); for the curves with a radius of 70 -642 ft, there was a considerable speed reduction at all speed levels;

(c) distributions for the side-friction coefficient (f) as computed using the curve geometric radius) showed that for the curves with radius > 640 ft, the mean values of f were equal or less than 0.12, with 20% of the value exceeding 0.15; for the 330 ft and 70 ft radius curves, 90% of the cars had f values > 0.15.

Emmerson (1970) extended the scope of his previous study by including more observations (12 curves with radii ranging from 25 - 460 m), using the same criteria for site selection and the same method of observation. The results showed that curves with radii > 200 m had little influence on speed, whereas there were considerable speed reductions at curves with radii < 100 m. These results were consistent with those of his previous study. A best-fit curvilinear relationship was developed between curvature and speed, giving a correlation coefficient of 0.98. The relationship was

$$v = 74\ (1 - \exp\ (-0.0017r))$$

where v = time-mean speed of cars, in km/h

and r = curve radius, in metres.

The curvilinear relationship was in sharp contrast to the linear relationship obtained by Taragin (1954). It should be noted that the curves studied by Taragin covered a broad range of minimum sight distance, (200 - 655 ft), whereas Emmerson considered curves with sight distance mostly in the vicinity of 500 ft or more. The sample size in Taragin's study was larger (35 curves in both directions, compared to 12 curves in 1 direction).

Information was not included as to whether the curves in Emmerson's study were transitioned. Therefore, it is not clear if the lateral shifts observed in many vehicles were the result of drivers doing their own transitioning of their path.

1.7.4 Department of Main Roads (DMR) Study

Speed measurements at the curve mid-point were carried out by the DMR (1969) at 21 sites on horizontal curves. The horizontal curves (radii 250 - 1500 ft) were chosen such that there was no sight distance restriction, uneven pavement surface or steep gradients and where cars generally could not cut corners. Speed was measured for about 40 to 70 cars for each direction with a radar speedmeter in the vicinity of the curve mid-point, during dry, daylight conditions. At a number of sites a series of pneumatic tubes connected to a time recorder were used to obtain speed trajectories of vehicles. SEE ERRATA

The results showed that:

(a) the 85th percentile speed at the curve mid-point was linearly related to the curve radius; the 85th percentile speed was considerably greater than the posted advisory speed for the small radius curves (250-400 ft radius);

(b) vehicles generally decelerated through the approach half of the curve reaching their minimum speed on the departure side of the curve; passenger cars tended to accelerate through the remainder of the curve, while commercial vehicles maintained the minimum speed.

(c) for curve radii > 1000 ft the mean friction factor was 0.12 or less; for curve radii < 400 ft, the mean friction factor was 0.21 or more;

(d) higher friction factor was developed on 'fine-grained' pavement surfaces than on coarse textured surfaces; greater road noise on the coarse textured surface was advanced to explain the lower observed speeds.

1.7.5 Glennon and Weaver Study

Glennon and Weaver (1971) observed speed and lateral placement trajectories of vehicles negotiating horizontal curves by means of cine-camera photography and a car-following technique. Five curves with curvature ranging from 2 degrees to 7 degrees (radii of

873 - 249 m or 2865 - 819 ft respectively) were studied. The lateral placement trajectories were used to compute the minimum path radius for each vehicle. The findings were as follows.

(a) The minimum path radius and the speed at which each vehicle negotiates the curve were uncorrelated.

(b) Most vehicles had path radii that were less than the road geometric radius at some point within the curve.

(c) The regions of highest side friction demands for most vehicles were in the first or last quarter of the curve; this was attributed to difficulties in making the transition from tangent to curve on the untransitioned study curves. The path radii at the point of maximum side friction demand were invariably smaller than the centre-line radius.

(d) The discrepancy between minimum path radius and curve radius increased with increasing curve radius.

1.7.6 Recent Australian Studies

McLean (1974) reanalysed the data from the studies by Taragin (1954), Emmerson (1969) and the DMR (1969) and produced the speed-curvature relationship as shown in Table 1.13.

EMPIRICAL SPEED-CURVATURE RELATIONSHIPS

Independent variable	Dependent variable		
	Taragin, 90th percentile speed (km/h)	DMR, 85th percentile speed (km/h)	Emmerson, median speed (km/h)
Curve radius R (m)	$59.1 + 0.065R$ $r^2 = 0.59$	$52.3 + 0.098R$ $r^2 = 0.91$	$40.8 + 0.097R$ $r^2 = 0.77$
$\sqrt{R}$	$43.2 + 2.10\sqrt{R}$ $r^2 = 0.67$	$31.7 + 2.95\sqrt{R}$ $r^2 = 0.90$	$25.9 + 2.62\sqrt{R}$ $r^2 = 0.88$
Curvature C (deg/100m)	$89.4 - 0.45C$ $r^2 = 0.74$	$93.1 - 0.55C$ $r^2 = 0.73$	$73.7 - 0.19C$ $r^2 = 0.87$
Exponential $V_o(1 - e^{-BR})$	$83(1 - e^{-0.014R})$ $r^2 = 0.73$	$89(1 - e^{-0.01R})$ $r^2 = 0.71$	$74(1 - e^{-0.017R})$ $r^2 = 0.95$

Table 1.13 Empirical Speed-Curvature Relationships (McLean, 1974).

Based on the proportion of variance accounted by the model (the r^2 value), it seemed there was a different model that fitted 'best' for each of the three data sets. It should be noted that Taragin's data were obtained from curves covering a broad range of minimum sight distance while the Emmerson and DMR data were from curves with relatively large minimum sight distance.

Regression of Taragin's speed data against the explanatory variables of curvature, pavement width, sight distance, superelevation, and side of the curve (inside or outside) showed that for mean speeds, only curvature and pavement width produced a statistically significant effect ($p < 0.05$), the relationship being a mean speed decrease with decreasing radius and pavement width. For the 90th percentile speeds, the effects of curvature, sight distance and lane location were all statistically significant ($p < .05$), the relationship being a decrease in the 90th percentile speed with decreasing radius and sight distance on the inside lane.

The side friction vs radius relationship was also investigated by plotting Taragin's 90th percentile side friction factors against the 90th percentile speeds, and the DMR's mean side friction factors against the mean speed. It was found that there was a considerable amount of scatter and only small proportions of the variances could be explained by a regression relationship. It was concluded that the operating speed was largely influenced by the curve radius rather than the side friction factor.

An ARRB study directed at investigating the relationship between vehicle operating speeds and the geometric properties of horizontal road curves involved collecting operating speeds (curve and approach) and road geometry data on 31 curves with speed standards nominally in the range 80 - 120 km/h, and on 41 curves with speed standards nominally in the range of 40 - 80 km/h (McLean 1976, 1978). Separate speed studies were made for each direction wherever possible, with each direction being considered as a separate study site. Free speed data were also collected at 20 sites on level tangent sections. The speed of effectively isolated (free) vehicles was measured by radar speedmeters, with the sample for each site typically comprising 50 -80 cars and 10 - 30 heavy vehicles.

Initial data appraisal (McLean, 1978) revealed that:

(a) the normal distribution provided a reasonable distribution of the observed speed;

(b) a strong correlation existed between the curve and approach speeds for individual vehicles; in general, vehicles with a high approach speed reduced speed on curves relatively more than vehicles with a low approach speed;

(c) for curves with design speeds greater than 90 km/h, the 85th percentile speeds tend to be less than the design speed, while for curves of lower standard the 85th percentile speed tended to be in excess of the design speed.

Regression analysis of the data for the 31 highway curves (radius 300 - 800 m) with speed standard in the range 80 - 120 km/h (McLean, 1976) showed that 71 percent of the variability in the 85th percentile curve speed could be explained in terms of curvature, sight distance, opposing flow and estimates of the desired travel speed, with curvature having the dominant effect. Superelevation was found not to have a statistically significant effect. The computed side friction factor (computed using the curve geometric radius) suggested that quite a few of the f values were above the design value ;the median value was 0.06 implying that the f values for the majority of vehicles were less than the design value. It was not clear if, and to what extent, the f values had been influenced by corner-cutting during curve negotiation.

The strength of the ARRB study was in the large curve sample size (about 120 sites). However the vehicle sample sizes at each study site were all less than 100 vehicles. The most important outcome of the ARRB study was that drivers did not traverse horizontal curves in accordance with the assumptions underlying the prevailing design policy. This resulted in the NAASRA departing from the design speed concept, as contained in the AASHO (1954, 1965) design documents and instead adopting a speed environment approach in horizontal curve design (NAASRA, 1980)

1.7.7 Stimpson, Kittelson and Berg Study

Stimpson, Kittelson and Berg (1977) measured speed and lateral placement at various sites with different alignments in order to establish the relationship between traffic performance measures and accident probability on two-lane rural roads. The speed and lateral placement at each location were measured using a pair of resistance-based electronic tape switches. The speed and lateral placement for the isolated horizontal curves (30 in the sample) were measured at the three locations (230 m before curve entry, at curve entry and at the curve mid-point). It was found that the mean and variance of speed did not vary significantly between the measurement locations within a given site or between day and night. However, lateral placement data indicated strong corner-cutting within the curve, the phenomenon being more pronounced under night conditions.

1.7.8 Lee Study

Driver speed behaviour approaching and traversing a curve was studied using the video-recording method (Lee, 1985). The study curve had a radius of 125 m with a superelevation of 6% and a design speed of 60 km/h, and was not transitioned. Approach vehicles were video-taped from 30 m before curve entry to 60 m into the curve (i.e. about half the curve length). The speed values were computed from vehicle travel time across 10 m road sections (graduated by means of markers placed on both sides of the road at 10 m intervals). Data were collected for a total of 400 passenger vehicles (lone or bunch leaders).

A broad range of vehicle speed was observed (50 - 90 km/h) with the mean speed 30 m before curve entry, at curve entry and at the curve mid-point being 79 km/h, 69 km/h and 76 km/h respectively. The minimum mean speed occurred 20 m into the curve. Different speed behaviour was observed between different drivers, with the faster drivers exhibiting more severe variations in speed. The average drivers tended to reduce speed more before curve entry than after curve entry; the reverse was true for the 85th percentile drivers.

The side friction factor f was computed using the curve geometric radius along every 10 m road section. The f values for the average and 85th percentile-speed drivers at the curve mid-point were 0.31 and 0.35 respectively. It was noted that 52% of the drivers had a vehicle path radius larger than the curve geometric radius. Depending on the degree of corner-cutting involved, the actual f values would be correspondingly less than that computed using the geometric radius. It should be noted that the curve was also joined at the mid-point by a minor road, and it is not clear how the presence of the T-intersection influenced driver behaviour through the curve.

1.7.9 Study Involving Instrumented Vehicles and/or Volunteer Subjects

The studies described in the previous sections can be classified as unobtrusive observations of drivers at horizontal curves. A few studies that involved using instrumented vehicles and/or volunteer subjects are briefly reviewed in the following paragraphs.

Ritchie, McCoy and Welde (1968) recorded speed and lateral acceleration for 50 subjects driving a 110 mile (175 km) course containing 277 curves. The subjects were instructed to drive 'normally'. Drivers were ranked by overall average speed for the course and placed in groups of ten, the fastest ten in group one and the slowest ten in group five. The mean lateral acceleration for each group was shown to be inversely related to the curve speed (i.e. for curves where the observed speeds were low, the observed lateral accelerations were high). Ritchie et al. suggested that the decrease in lateral acceleration as speed increased reflected driver perception of increasing danger, but an alternative explanation could be that the higher speed was associated with higher standard curves where drivers were less likely to exceed the design speed, because their desired speed would be close to the design speed.

Herrin and Neuhardt (1974) recorded speed and lateral acceleration for 2 groups of 10 subjects driving over predefined routes on two-lane rural roads. The first group repeated a 9 mile (14.4 km) route four SEE ERRATA times, encountering 10 well-defined curves; the second group made two runs over a 14-mile (22.4 km) route with 15 principal curves. On different runs, drivers were told to drive according to either "scenario A: drive as though your are late" or "scenario B: drive as though you are on a leisurely Sunday afternoon drive". Data were grouped according to these scenarios. The results showed that driver's tolerance of lateral accleration is not constant but changes with the driver's needs and the situation. A driver "in a hurry" was shown to tolerate a higher lateral acceleration than one on a leisurely drive, and a driver familiar with the roadway tolerated and drove at a speed that would result in a greater lateral acceleration than a driver unfamiliar with the roadway.

Johnston (1983) investigated the effects of alcohol on driver performance at a test-track that was treated with nine different roadway delineation types, each applied along the entire test track for each test. Drivers with blood alcohol levels of zero and 0.05% drove an instrumented vehicle with a microprocessor-based data logging system. The study showed that alcohol had a negligible effect on the mean speed but increased the incidence of extreme lane positioning at the curve mid-point and led to more frequent departures from the lane. Extremely overwhelming evidence of corner-cutting was found.

There have been many studies that are related to human behaviour at horizontal curves that were from SEE ERRATA different perspectives. These studies included investigations of matters such as the attentional demand of curve negotiation (e.g. McDonald and Ellis, 1975), eye movements during curve negotiation (e.g. Shinar, McDowell and Rockwell, 1977), and misperception in curve negotion (e.g. Shinar, Rockwell and Malecki, 1980). Vehicle control during curve driving has also been studied and steering behaviour models developed (e.g. Donges, 1978; Reid, 1983; Godthelp, 1986). Research on driver behaviour modification on curves has appeared frequently in the safety literature (e.g. Johnston, 1982). It is however beyond the scope of this project to examine all the facets of driver behaviour on horizontal curves, and the main thrust will be on unobtrusive investigation of driver behaviour on horizontal curves, before and after realignment.

1.7.10 <u>Discussion</u>

The results of the studies that have been reviewed in the previous sections are summarised as follows.

(1) There are relatively few studies that involved unobtrusive observation of driver's behaviour on horizontal curve. The main emphasis in such studies has been on how the spot speeds at the mid-points of isolated horizontal curves are related to the curve design features. Vehicle samples were mainly free vehicles (i.e. lone vehicles and bunch leaders) with data collection usually carried out in dry, daylight conditions.

(2) There has been particularly little research on identifying vehicle trajectories and variations in path radius along the trajectory. Hence practically all the computation of sideway force coefficient f has involved using the curve geometric radius rather than the actual path radius.

(3) The unobtrusive observation of operating speed has showed the following results.

(a) Curvature has a dominant effect on the in-curve operating speed; speed at the curve mid-point is strongly correlated with the curve geometric radius (Taragin, 1954; Emmerson, 1969; DMR, 1969; McLean, 1976). The tendency is for higher speeds on larger radius curves. A linear relationship was proposed by Taragin, DMR and McLean and a curvilinear relationship by Emmerson.

(b) Speed inside the curve is influenced by the minimum sight distance (Taragin, 1954; McLean, 1974; McLean, 1976). The tendency is for higher speeds for higher minimum sight distance. Taragin estimated the effect of minimum sight distance to be about a third of that due to curvature, while McLean(1976) showed that sight distance had some minor explanatory effect.

(c) Speed inside the curve may not be significantly affected by superelevation (Taragin, 1954; McLean, 1976).

(d) Speed inside the curve may (McLean, 1974) or may not (Taragin, 1954; McLean, 1976) be significantly influenced by lane position (inside/outside). Taragin indicated no significant difference between the inside and outside lanes while an analysis of Taragin's data by McLean (1974) suggested higher 90th percentile speeds on inside lanes. McLean's later (1976) analysis of speed data for high standard curves showed lane position had no statistically significant effect.

(e) Speed may (McLean, 1976) or may not (Tharp and Harr, 1965) be affected by the presence of opposing vehicles. McLean's results indicated an inverse relationship between speed in a curve with the level of opposing flow, while Tharp and Harr showed that the general trend of the speed profile along the approach and in the vicinity of curve entry was not affected by opposing flow.

(f) Speed may (McLean, 1974) or may not (McLean, 1976) be influenced by lane width. McLean's reanalysis of Taragin's data (McLean, 1974) implied a smaller mean speed for a narrower lane. McLean's (1976) results showed that lane width had no statistically significant effect.

(g) Speed at the curve mid-point can be represented by a normal distribution (McLean, 1978).

(h) Speed inside a curve is influenced by the desired travel speed (McLean, 1978). For high standard curves (design speed of

90 km/h or more), the 85th percentile speed tends to be less than the design speed while for low standard curves the 85th percentile speed tends to be more than the design speed.

(i) Speed inside a curve is influenced by the approach speed (Tharp and Harr, 1965; McLean, 1978; Lee, 1986). Speed adjustment seems to commence earlier for smaller radius curves (Tharp and Harr); vehicles with a high approach speed tend to reduce speed more (McLean); the average driver was shown to reduce speed more before curve entry than after curve entry, but the reverse was observed for the 85th percentile driver (Lee, 1986).

(j) The proportion of vehicles exceeding the design speed was significant for curves with radius <120 m (Emmerson, 1969; DMR, 1969; Lee, 1986).

(k) The speed profiles have been shown to be approximately constant within the curve by Taragin (1954) but this finding is not supported by the results of Tharp and Harr (1965), DMR (1969) and Lee (1986). The non-constant profiles indicate that passenger cars tend to commence acceleration once the minimum speed is reached, while heavy trucks maintain the minimum speed. The minimum speed was generally observed on the departure side of the curve in the DMR study, while the minimum mean speed in Lee's study was observed in the first quarter.

(4) Corner-cutting is prominent, especially on small radius curves (Emmerson, 1969; Glennon and Weaver, 1971; Stimpson et al, 1977; Lee, 1986). Emmerson estimated that 10% of cars cut corners and that many cars had lateral shifts of 2-3 ft. Lee reported 52% of his sample had path radii greater than the geometric radius for his study curve (radius of 125 m). Stimpson et al. observed that corner-cutting tended to occur within the curve and was more pronounced at night. Glennon and Weaver showed that most vehicles had path radii less than the geometric radius at some point within the curve and the discrepancy between minimum path radius and curve radius increased with increasing radius.

(5) Minimum path radius is not correlated with speed (Glennon and Weaver, 1971).

(6) The sideway force coefficient f values increase as radius decrease (Taragin, 1954; Emmerson, 1969, DMR, 1969; McLean, 1974). For curves with radius <100 m, a significant proportion of drivers had f values > 0.15 and for curve radius > 300m the majority of drivers had f values < 0.15.

(7) The f values are affected by surface type (DMR, 1969). Higher f values are associated with smoother-textured pavements.

1.8 THE PRESENT STUDY

Having considered the various safety-related issues, related to human factors in road safety and driver behaviour at horizontal curves (as discussed above), it was decided to undertake a study involving unobtrusive observation of driver behaviour on two curves before and after realignment. A 'before and after' approach meant that evaluation of the realignment could be carried out without the need to control for 'external' factors, such as traffic flow characteristics (e.g. flow rate) and the general operating environment (e.g. land-use patterns, the condition of the road network in the vicinity). The two sites involved an isolated horizontal curve and a reverse curve. The physical characteristics of the two sites are described in detail in Chapters III and IV respectively.

The method used for the unobtrusive observation was continuous video-recording of vehicle movement at the study site using a series of video cameras. The video cameras were carefully camouflaged. Vehicle movements were video-recorded sequentially as subject vehicles moved through the curves. Lateral placement and speed data were extracted from the video records. A detailed discussion of the various aspects of the field work, as well as the subsequent data extraction and analysis, is contained in Chapter II. The results for the isolated curve are presented in Chapter III while the results for the reverse curves are contained in Chapter IV.

In Chapter V the results of the study are compared with designer expections of driver behaviour at horizontal curves, in order to check the appropriateness of underlying design assumptions. The before and after results are used for evaluating the realignment, especially in terms of the observed driver behaviour. The observed driver behaviours are also discussed.

CHAPTER II

2.1 COLLECTION OF CURVE DATA

2.1.1 Preparing the Site

As the sites under under study were to be re-aligned, construction plans (scale 1:500) were available from the Ministry of Works and Development. The construction plans were used as working plans for the field data collection. Design parameters were available for re-aligned curves only.

Site surveys were carried out to determine the mid-curve point and the bounds of the curve, to divide the curve and adjoining tangents into equal segments, and to look for suitable support structures for video cameras.

The apex point was determined by locating the imaginary intersection point of the extrapolated edge-lines of adjoining tangents (point I in Figure 2.1). This imaginary point was estimated by an observer standing on the outside of the curve and adjusting his position such that he could look straight down both tangent edge-lines. The point on the centre-line that was nearest to the observer was then taken to be the curve mid-point (point M in Figure 2.1). The point at which the edge-line changed from straight to curvilinear was designated the physical bound of the

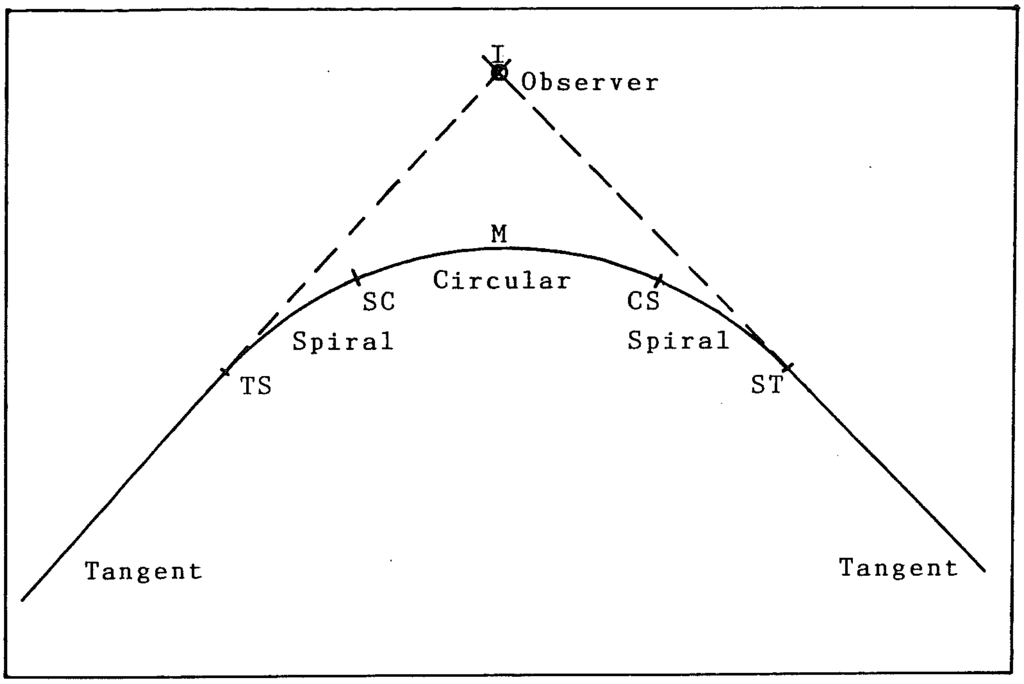

Figure 2.1 **<u>The Different Points of the Curve</u>**

curve, equivalent to the tangent-spiral point (point ST, TS in Figure 2.1). The tangent-spiral points so obtained were found to approximate very closely to the as-designed tangent-spiral points of the reconstructed curve, confirming the validity of using the estimation method described above.

Pavement delineation lines provided references from which measurements were made. The delineation lines are edge-lines, which are continuous white strips of 75 mm width, and a centre-line, which is a broken line represented by intermittent white strips 3 m x 100 mm with 7 m gaps. The centre-line was marked (by spray painting) at equal intervals, starting from the curve mid-point, to the maximum distance that could provide a large enough picture (as recorded by video camera) for accurate data extraction. At each centre-line mark, corresponding marks were made on the left and right edge-lines such that the three points formed a control cross-section (as shown in Figure 2.2). It was at these control sections that time and space measures, for determining speed and lateral wheel placement respectively, were made.

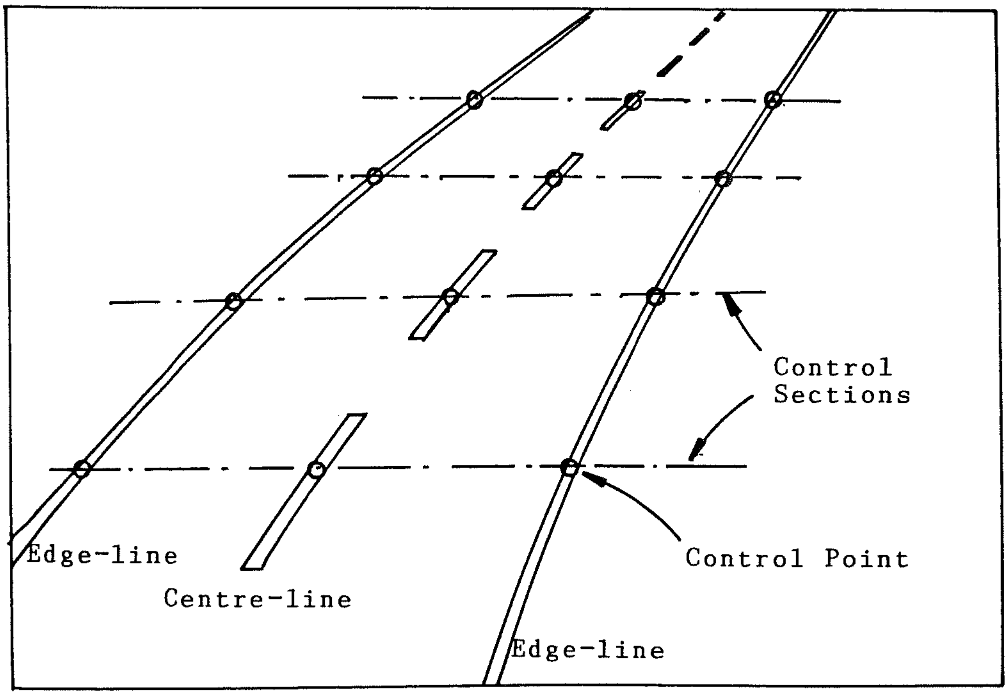

Figure 2.2 Control Points and Control Sections

Choosing the spacing between adjacent control sections involved a trade-off between time required for data extraction and the amount of information to be extracted along the curve. Closely spaced control sections would have provided information at more points along the curve but at the expense of a greater data extraction time. A "minimum of 10 observation points within the curve bounds" was the criterion used to calculate the maximum spacing values for curves of less than 100 m length; for longer curves, the spacing was set at between 10 to 15 m.

Measurement along the centre-line was done using a measuring wheel. All the control points for the control sections were identified by spray painted crosses on the centre- and edge-lines.

During the site survey, suitable support structures for cameras and bushes to camouflage cameras were identified. This information was used to plan the video recording exercises later on.

2.1.2 Superelevation

Superelevation values at the control sections for the study sites before re-alignment of the curves were obtained from field measurements. The design superelevation values were used for the study sites after re-alignment.

Field measurement for superelevation involved using a surveyor's level to obtain height difference (to within 1 mm accuracy) between control points at centre-line and edge-line, and a cloth tape to measure the distance between the control points. Two sets of measurements were made at each control sections, one for each lane. The ratio of height difference over horizontal displacement gave superelevation values. Typical values were between 0.03 to 0.06, implying a relatively small height difference over a large horizontal displacement.

2.1.3 Radius of Curvature

Radius of curvature was obtained by field measurements for the before-study curves. For the after-study curves, the as-designed radii were available.

The method of determining the radius of curvature in the field was by measuring the sides of the triangle formed by three consecutive control sections at a delineation line and calculating its circumscribed radius. This circumscribed radius was assumed approximately equal to the radius of curvature at the middle section.

Measurement was done on the triangle formed on the outer edge-line so as the minimize disruption to traffic flow. Chaining tripods were positioned, with the aid of plumb-bobs, above the three corners of the triangle and measurement between each pair of tripods was made with a steel band (of the type used in catenary surveying).

2.1.4 Stopping Sight Distance Survey

Stopping sight distance (SSD) was measured in the field at selected control sections where there was restriction on stopping sight distance posed by obstructions on the inside of the curve. SSD (as defined by current New Zealand practices) is the maximum distance measured along the middle-line of a lane at which an observer standing in the middle of the lane can see, at an eye height of 1.0 m, a stationary object of 0.15 m height that is positioned in the middle of the same lane further ahead. In design work, SSD is normally checked only for the inside lane of a curve since the outside lane would theoretically give a longer SSD. However in this project it was found useful to measure SSD for both inside and outside lanes (i.e. for both directions of travel). SSD as defined above can be interpreted as a measure of sight obstruction on the inside of the curve.

The method employed to measure SSD was to have an observer standing in the middle of the lane at a control section and peering down the road ahead at an eye height of 1.0 m. An assistant carrying a vertical length of 1.2 m x 0.2 m matt black board with the bottom 0.15 m sprayed in reflectorized yellow paint moved away from the observer till a point was reached when the upper reflectorized part of the board was obscured. The position of the assistant in the middle of the lane was marked. A measuring wheel was rolled along the middle-line of the lane from observer to assistant (or vice versa) to obtain the SSD at the observer's position. The same procedure was repeated for other control sections, and profiles of SSD were plotted for both directions of travel.

2.1.5 Skid Resistance

Skid resistance measurements were carried out at a number of spots within the study curves. Because of limitations on sight distance, measuring skid resistance along the curves tended to be hazardous. In New Zealand, it is not a standard practice to close off one lane for taking such measurements.

The skid resistance was measured using a portable British Pendulum skid resistance tester, in accordance with the standard procedures described in Road Note No. 27 (DSIR, 1960). A sand-patch method (also described in Road Note No. 27) was also performed, to measure the surface macro-texture.

2.1.6 Speed Surveys

A number of speed surveys were conducted along the adjoining tangents at the Foremans Road study site. Speed surveys were done along the tangents at both ends of the curve both before and after re-alignment (i.e. 4 surveys).

The method used in the speed survey was measuring of the time taken for a vehicle to traverse a 25 m stretch of road. This was achieved by laying 2 pneumatic tubes 25 m apart, with the tubes being connected to an electronic device, with the pressure pulse from the upstream tube acting as a triggering device and the downstream tube providing the detriggering pulse. An electronic clock timed the open-close cycle to the nearest one-hundredth of a second. A digitector, based on the same principle but giving speed directly in km/h, was used in the before study survey. In each speed survey, the tube mechanism was checked against values obtained by a microwave radar-scope. Based on a sample of 30 vehicles, the values obtained by the pneumatic tube methods and the radar-scope were found to differ by around 2%.

The speed survey was carried out to establish the operating speed environment along the adjoining tangents of the Foremans Road curve in the before and after periods.

2.2 VIDEO DATA COLLECTION

2.2.1 Equipment for Video-Recording

The equipment used for video recording was a video tape recorder (VTR), a modified sequential switcher, three colour video cameras, a black-and-white (B/W) monitor, and coaxial and 10-pin connecting cables. In addition, a B/W video camera was used in conjunction with a TR6 traffic speed radar whenever the latter was available. The power requirements were supplied by 12V, 9-plate lead-acid batteries (DC power) and a portable generator (AC power). The equipment was set up as shown in Figure 2.3.

The VTR was a Panasonic AG-6010 VHS time lapse recorder with a horizontal resolution of 240 lines for colour and 300 lines for monochrome. The VTR could record and play back in four different time modes - normal (3 hours), 18, 36, 72 hours. Useful features included a time-date generator, reverse playback, fast forward/reverse, forward/reverse frame shift and noiseless still frame.

The switcher was a National WJ-512 auto-alarming sequential switcher, which was modified to provide 'genlocking' of colour video cameras, as well as allowing superimposition of the video signal from a secondary B/W camera onto the video output of the switcher. Genlocking is a method of synchronizing

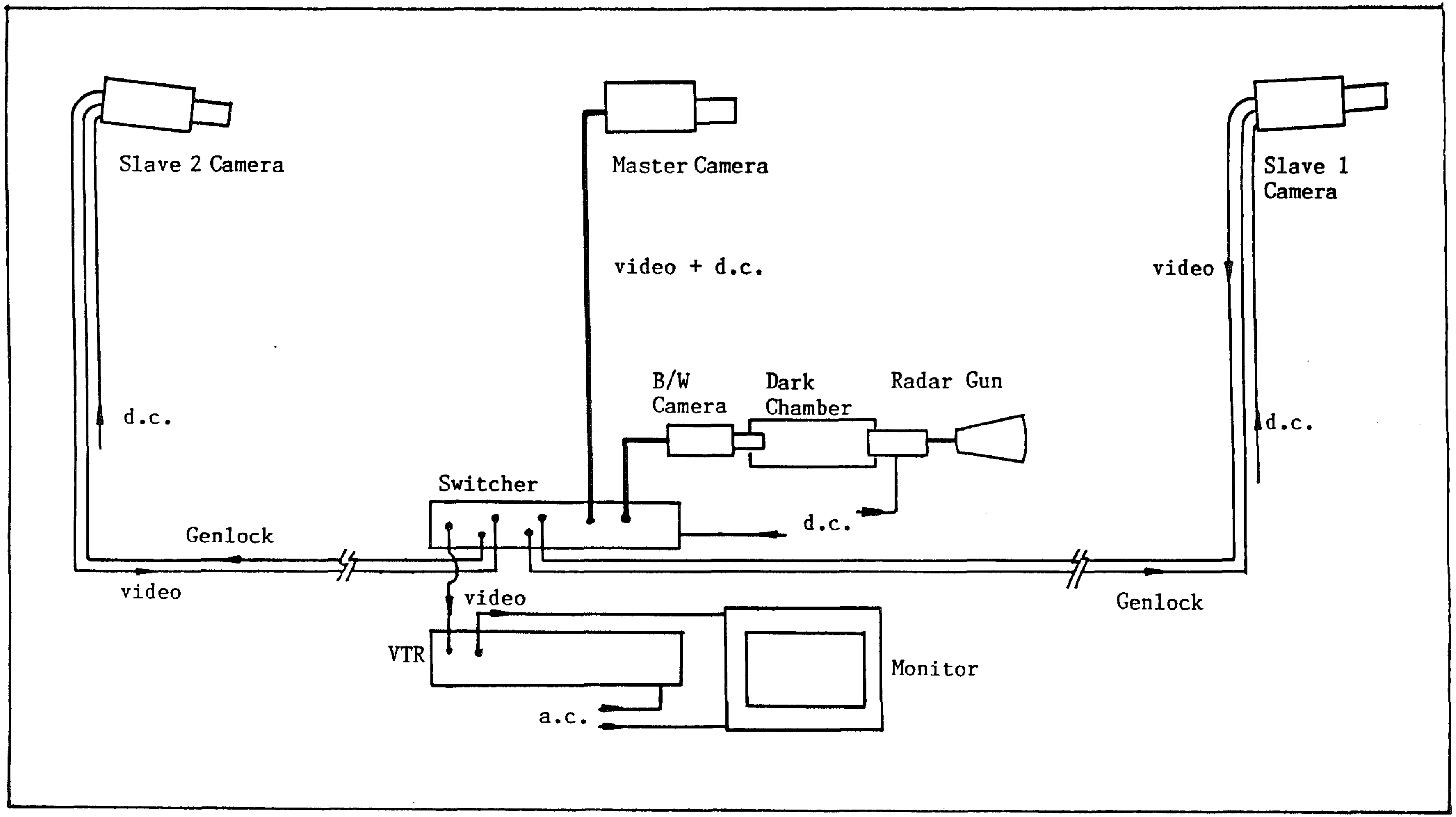

Figure 2.3 Equipment Layout for Driver Behaviour Data Collection

two or more cameras whereby the cameras' internal synchronizing pulse generators are locked to an external video waveform. Synchronization, is necessary for stable mixing of different videos such that no information is lost during the change-over period e.g. switching from one camera to another. Without synchronization, there would be about half a second of disturbance while switching. Superimposition was used for inserting the speed display , as read by a B/W camera from the radar gun, onto the video output.

Up to three colour video cameras (National WV-3600 N) were used for field data collection. Each camera used a single vidicon tube with scanning standard of 625 lines, 50 fields and 25 frames per second and produced internally synchronized PAL (Phase Alternation Line) composite video with horizontal resolution of 250 lines (at centre). (A composite video is a video signal which includes both picture and synchronizing information. Composite video signals from different sources need to have their synchronizing pulses 'in-step' with each other for stable mixing). The National WV-3600 N cameras accepted composite black burst signals through the genlock input for synchronization. Zoom lens (6 x 16 mm) with auto/manual iris were used with the camera heads.

A B/W monitor (16 inches) was used to selectively view the picture from any of the colour cameras, the input signal having been chosen by the switcher and looped through the VTR. This preview on the monitor was necessary for setting up the camera, to ensure a complete record of a vehicle traversing the curve was obtainable, and to check that camera positions had not changed.

Signal transfers between the various components were piped through 75 ohm coaxial cables, apart from the connection between the 'master' camera and the switcher, which was a 10-pin cable. This included two-100 metre length coaxial cables (one for the video signal and, one for the synchroniation signal) to each of the far (slave) cameras. No connections were made for audio recording .

During the early part of the data collection exercise, a Kustom TR-6 traffic speed radar was available on loan from Ministry of Works and Development. The TR-6 gave vehicle speeds, output via an LED display. A B/W video camera read the LED speed display in a darkened chamber, and this secondary B/W video signal was inserted onto the main colour video signals. The net result was colour pictures with speed readings.

Of the equipment described above, the VTR and monitor ran on a.c. power while the cameras and switcher used d.c. power. The a.c. power was supplied by a portable Honda EX650 generator which had a rated output of 450 VA at 50 Hz. The cameras were set up at great distances apart (up to 100 m) so it was most practical to have a separate d.c. power source for each camera. Car batteries (12 v/ 9 plates) were used to supply d.c. power so as to ensure an adequate supply for up to 10 hours uninterrupted camera operation.

A host of supporting gear was also brought to the site. These included a light-weight step ladder, a tent, supports for video cameras (tripods, pan/tilt heads), a marker board, and a spare car battery. Lack of suitable storage facilities at the study sites necessitated transportation of all gear between the University and study sites for each recording session. A small station wagon with a mounted roof rack was found to be adequate for transporting all equipment.

2.2.2 Setting Up

Setting up involved putting the colour video cameras in the proper positions (the major task) and making connections to link the various components.

The camera set up was determined by the type of perspectives required, which were in turn dependent on the type of data to be extracted. In this project, the primary data were vehicle lateral displacement from the centre-line and forward velocity at control road cross-sections. The control sections were located at regular intervals such that all were within full view of a camera. During data extraction, the control sections were plotted as perspective horizontal (or near horizontal) grids with each grid graduated to scale; the time of crossing and the lateral displacement of each subject vehicle across the grids were measured as a subject vehicle crossed each successive grid. The perspective views recorded therefore had to be suitable for accurate location of grids during grid construction, as well as showing distinct crossings of vehicle at the grids during data extraction.

Elevated views, taken from the maximum possible elevation, best satisfied the above requirements. In addition, a frontal view (front-on to the line of approaching/departing traffic) was attempted, whenever possible, to minimise the effect of camera image retention. (Image retention is most pronounced for objects moving at a high speed across the field of view. The effect during still playback is blurred multiple images). A frontal view also covered a greater length of road, minimized obstruction of far lane traffic by near lane traffic and showed control road cross-sections in a horizontal orientation (and able to be represented as horizontal grids during playback). As any horizontal line in an oblique photograph is a line of constant scale (which is a basic principle in the construction of a perspective grid in photogrammetry), a horizontal grid can be calibrated by knowing the distance between any two points on the horizontal control section.

To obtain good elevated frontal views, the cameras were mounted as high as possible and facing front on (where possible) to the line of the moving traffic. Various supports were used including, in order of preference, on telegraph and power poles, on tree trunks and sturdy branches, inside or on a box on high ground, on top of a step-ladder, and on tripods. Where supporting structures were telegraph/power poles or tree trunks/branches, cameras were mounted on friction pan/tilt heads which in turn were attached to frames that were clamped to the supports. The frames could be rotated, by inserting pegs, to tilt cameras to adjust for supports not being horizontal. Hence cameras could be orientated in 3 dimensions to get desirable perspectives.

The choice of supports was further influenced by camera-to-camera spacing and the prospect of camouflaging the set-up. Camera spacing was determined by 3 factors: the scale of the horizontal grids (representing selected cross-sections) in the playback pictures (a video projector was used during playback, giving a picture size of 210 cm x 143 cm), having a sufficient overlap in the pictures between adjacent cameras, and the length of the connecting cables. A trial run established that the working scale should be larger than 1:10, with an absolute lower limit of 1:15 being acceptable in cases where a highly elevated frontal view was attainable. For a scale smaller than 1:15, the error in the data was very much influenced by the resolution of the picture as it became increasingly difficult to pin-point the vehicle position. Good overlap between cameras was the key to maintaining an unbroken tracking sequence of the vehicle under observation. Camera-to-camera overlap was of the order of 2-4 grids. In the data collection exercise, camera spacing was usually in the range of 50 m to 80 m with a maximum spacing of 100 m (the video signal would have required amplication if the distance had been much greater than 100 m).

Camouflaging of the set-up was an important aspect of the study because the primary objective was unobtrusive observation of driver behaviour during curve negotiation. A layout that was visible to the drivers would be expected to alter the pattern of behaviour under observation. Further, a conspicuous set-up could well distract the drivers' attention from the driving task, and hence could increase the probability of making errors and the risk of accidents.

In general, camouflaging was applied to the camera set-up, mainly because the other components were at ground level and housed in a New Zealand Post Office (NZPO) workman's tent some distance away from the pavement. The NZPO tent was a ideal choice because of its small size as well as being commonly seen at the road side by road users. Camouflaging involved placing cameras in suitable surroundings such as roadside vegetation (natural or purposely assembled) and against a suitable background (a dark background making the camera least easily discernible).

After the supports had been selected, the cameras were mounted and then adjusted, with the aid of electronic viewfinders, to obtain relatively large scale (>1:15) elevated frontal perspectives that gave uninterrupted tracking of the vehicles under observation. The cameras were then linked to the VTR via the switcher,which was located near the 'master' camera (see layout diagram). From the preview on the monitor, a final check was made on the quality of the pictures from each camera. A check was also made on the adequacy of overlap between adjacent cameras. Once video recording had begun, the camera positions and adjustments were not to be altered throughout the session. The monitor enabled checking of camera positions.

2.2.3 Video Recording

Video recording comprised two phases: a calibration phase and a data collection phase. Each recording session had to contain the two phases to be suitable for subsequent data extraction.

The calibration phase was concerned with recording marker board positions at the centre-line and edge-line points of each control cross-section. The marker board was a 90 cm x 40 cm white-painted board bisected (along the long side) by a black-coloured inverted arrow head. During calibration, the tip of the arrow head was lined up against the control point on the pavement as the board was placed facing the camera. Calibration was carried out at the beginning of the recording session to safeguard against weather conditions deteriorating as recording progressed as well as providing a further check on the overlap of the cameras.

During the data collection phase, camera outputs were selected for video recording. This was done through manual switching, with the preview on the monitor providing the cue as when to change input channel. The VTR was activated to normal recording mode only when there were suitable subject vehicles being tracked. During other times (e.g. during quiet periods), the VTR was either in pause or in time-lapse mode. In this way, a 3-hour tape was adequate for recording over a 5 to 7 hour period.

Selection of suitable subject vehicles for recording was done as follows: lone vehicles or platoon leaders, traversing in either direction, and appearing on video along the full length of the road section under study, were selected for recording. The criterion for distinguishing between lone and platoon vehicles was a headway of greater that 4 second for lone vehicles. The presence of pedestrians (e.g. hikers), as well as an overtaking manoeuvre by any vehicle within the study zone (or within 50 metres from the study zone) also disqualified prospective subject vehicles. Within these constraints, the strategy employed was to video record as many vehicles as possible, irrespective of time of day, density of flow or class of vehicle.

An on-going task during video recording was to check if there had been any shift in camera position. This was done by attaching transparencies on the monitor screen and masking in identifying spots from the picture of each camera prior to commencement of recording . Any subsequent shift in camera position would then be highlighted by a mismatch of the identifying spots. A shift in camera position after the calibration phase was equivalent to a mismatch between calibrated grids and the playback pictures that was recorded in the 'new' camera position. A temporary shift (e.g. one caused by a transient wind gust) could be corrected by simply ignoring that segment of data during data extraction. A permanent shift such as slippage at the pan/tilt head would necessitate another calibration if video recording was to continue. (It was found to be impractical to put the camera back to the original position since the video recording was carried out by one person alone).

Recording was carried out during daylight hours and in dry weather since the cameras required a minimum illumination of 1400 lux and less than 90% ambient humidity for satisfactory operation. A windless condition was also necessary to maintain still camera position. A few recording sessions were abandoned as a result of wind conditions getting too strong as recording progressed. An overcast sky was also preferred to bright sunshine. In bright sunshine, the reflection of light off glass surfaces produced very strong glare which could have damaged camera tubes. This was especially serious when the sun had moved to a near vertical position above the cameras (i.e. around midday). Recording was temporarily stopped around midday when the sunshine was strong. Bright sunshine also produced a higher brightness ratio (the ratio between the brightest and darkest part of the scene) and this increased the effects of blooming. Blooming is the masking of darker signals by brighter signals, with the result that the brighter part of the scene creeps into the darker area, making the location of the boundary inaccurate. Hence, a black object would appear smaller against the white background and a white object would appear larger against a dark background. In this project, the high brightness ratio between the white edge-line and the dark pavement helped to make construction of the grids an easier and more accurate task. Blooming did affect the accuracy of the wheel displacement data but this effect was considered minimal, since the contrast between the pavement and wheel was rather small.

The length of a recording session varied between two to three hours of normal mode recording over a single day period, weather permitting. It was difficult to have more than three hours of recorded data, partly because of the great amount of time necessary to complete the equipment set-up, and later to collect and pack the gear (one and a half hours for each operation for one person).

2.3 DATA EXTRACTION

The data process involved the construction of perspective grids, and extracting data during video play back sequence. The set-up comprised the following: a video-recorder linked to a video data projector, a screen on which the perspective grids were constructed and a computer terminal for entering extracted data. The video recorder was the same unit as that used for field recording. The video data projector was a Sony Multiscan projector. The computer terminal was connected to a VAX 11/760. It was established in preliminary data extraction trials that a television/monitor screen was less suitable for the data extraction because the small scale gave a very cluttered grid pattern, with the precision of measurements being substantially less than when using the video projector.

2.3.1 Perspective Grid Construction

The control road-sections in the study zone were represented in two dimensions as perspective grids. Each grid was plotted on the screen by locating the marker board positions on the edge - and centre-lines. The grids were then calibrated by scaling the width of the grids to the width of the corresponding control sections. The method of linear scaling was used as each grid was of constant scale.

The grids were constructed on a plain screen. The projected screen dimensions were 210 cm by 143 cm (254 cm along the diagonal), which was more than 4 times larger than a 24-inch (61 mm) monitor. This SEE ERRATA. large scale allowed construction of all the grids (for each recording session) on a single screen. Each camera had a corresponding set of grids in the section of road covered by that camera. Hence the screen was filled with up to three sets of grids, with grids crossing each other. For ease of identification, each grid set was drawn in a colour which was different from the other sets.

A most important task before taking data off the screen during playback was to ensure that the constructed grids were accurate in relation to their spacing and their lateral calibration. Spacing was tested by observing the time slices required to traverse between adjacent pairs of grids. Any two adjacent grids that were constructed too close together would reveal a distinctly shorter traverse time at the expense of the neighbouring pairs of grids. The accuracy of the calibration across each grid was checked by observing vehicle width at each grid. For a particular vehicle, this width should be a constant across all the grids.

The short distance between adjacent control sections (10 or 12.5 metres) implied a very short traverse time, thereby making accuracy in determining traverse time very sensitive to accuracy of grid spacing. For example, the traverse time for a distance of 10 m at a speed of 90 km/h is 0.4 seconds or 10 video frames. This problem was compounded by the front-on camera position which made the determination of when the wheel was on the grid more difficult. In addition, the video recording format was at a discrete interval of 0.04 second, which made it usually necessary to estimate, to the nearest frame, the longitudinal wheel-on-grid position. In contrast, the front-on camera position meant that vehicle lateral position across the grids was not sensitive to accuracy of grid spacing, which in turn meant higher accuracy in the determination of lateral displacement.

Apart from testing the accuracy of perspective grids before commencing taking data, special attention needed to be paid to the problem of shifting of the camera position during the video recording period, in so far as the constructed grids were true only for the calibration phase of video recording using marker boards. As the grids were only imaginary lines constructed for the convenience of data extraction, they were not suitable for detecting shifts in camera position. To overcome this problem, the road delineation lines as well as prominent features in the scenery eg. trees, fence-lines and posts were also drawn onto the screen. These 'marker' positions were also essential for re-establishing data projector position especially when the projector had to be taken away or the set-up had to be dismantled for other laboratory users.

2.3.2 Extracting Data

Taking data off the screen during playback was by far the most time consuming task of the whole project. This was because the whole process required the operator to manually note the time interval for a subject vehicle to cross each pair of grids, as well as determining its lateral wheel position across every grid. Other parameters that were noted were the type of vehicle, its direction of travel, its front/rear wheel-to-wheel span (outer faces), whether it was alone or a platoon leader, vehicular activity in the adjacent opposing lane and the time of the day.

The detailed data extraction procedure was as follows. For each prospective subject vehicle, a preliminary playback run was made to ensure that its path was recorded along the complete stretch of road covered by the cameras and it was not at any stage obscured by other vehicles at the grid lines. Camera shift, highlighted by mis-match in 'marker' positions, was also checked. This qualifying round was done at normal playback speed. For vehicles that qualified, the video tape was rewound to the position where the subject vehicle was about to cross the first grid. By means of slow speed playback (12 or 24 times slower) and pausing at grid lines, with the occasional forward/reverse frame shift, the number of frame advances between each pair of grids and the lateral position of the outer face of wheel at each grid were noted and entered directly into a computer file. These data were used for computation of speed and lateral placement. It should be pointed out that a radar was used for speed measurement for the adjoining tangent section during the early phase of data collection but a suitable radar was not available during the later phase. For the curved road section, radar was not used because of the need for making a correction for deviation from head on angle, as well as requiring a much higher level of sophistication in the video recording equipment to incorporate superimposition at each camera. It was also unfortunate that a suitable time base which could give time to within one-hundredth of a second was not available for data collection. Subsequent attempts to add such a time base through the video character generator produced deterioration of the picture quality, and this approach was not pursued.

For both time and space measurements, the chosen vehicle point of measurement was the outer face of the wheel nearest to the cameras (front wheel for approaching vehicles, rear wheel for departing vehicles). However this point of measurement was quite often not well defined in the playback pictures. The problem of poor definition was most acute when the wheel was in a dark shadow (caused by strong illumination) which decreased the level of contrast between wheel and pavement. In such situations, other parts of the vehicle (such as lights and bumpers) were used to help estimate the position of the outer face of the wheel.

At the conclusion of extracting all the data for each vehicle, a program to calculate and display the vehicle speed and lateral displacement profiles was run so as to detect any inconsistent data point (eg. very sudden peak or trough). The profiles were instrumental in highlighting error while reading off the screen or in coding.

Data for other parameters were much more straight-forward. The time of the day was read off the built in time-date indicator. The front/rear wheel-to-wheel span was usually taken in the foreground grid where the scale was largest. The level of activity in the opposing lane was recorded; if there was an opposing vehicle, the vehicle type and the point at which the opposing vehicles passed the subject vehicle (to the position of the nearest grid) were recorded.

2.3.3 <u>Time required for data extraction</u>

The time involved in data extraction was of the order of 5 observations (i.e 5 subject vehicles) per hour, with each observation having up to 26 pairs of data points in time and space measures. A fair amount of time was also spent in constructing and 'fine-tuning' the perspective grids (10 to 12 hours). As the data projector was on loan on a daily basis, an hour was also spent in setting up the data projector and other equipment before data extraction could begin. The data extraction from the video records produced, for each subject vehicle, data with the following attributes:

(a) time of recording;

(b) number of video frames between each pair of grids; this number was assigned to the second grid eg. if 10 video frames between grid (n-1) and grid n then the quantity 10 was assigned to grid n (the frame count for grid n);

(c) lateral displacement from the centre-line at each grid, with reference to a measurement point on the vehicle;

(d) type of vehicle (van, car, utility, small truck etc.);

(e) status of subject vehicle (lone or platoon leader);

(f) wheel span (outer face to outer face);

(g) vehicular activity in the opposite lane (vehicle type and location of vehicles meeting).

Of the above information, only (b), (c), (f) and (g) were used in subsequent analysis. The sample sizes were considered too small for analysis by vehicle type. Preliminary analysis also indicated that the effect of lone versus bunch-leader vehicle type on vehicle performance at the Foreman's Road Curve (See Chapter III) was relatively small; the proportion of bunch-leaders at the Leithfield study site (Chapter IV) was less than 20 percent of the total sample.

2.4 DATA ANALYSIS

The analysis of data involved 2 phases:

(1) transforming the extracted data to a form suitable for statistical analysis; the output is called the reduced data;

(2) analysis of the reduced data using the SAS statistical package.

2.4.1 Transforming the Extracted Data

This phase was carried out using programs written specifically for reading and transforming the extracted data to produce reduced data. The following are the definitions of the basic terms used in the remainder of the thesis.

Vehicle Measurement Point: the point on the subject vehicle to which the lateral displacement (see below) was made. The vehicle measurement point could be at any of four vehicle wheels.

Vehicle Lateral Displacement: the distance from the centre-line to the vehicle measurement point.

Vehicle Reference Point: the point on the subject vehicle to which the lateral placement (see below) was referred. The vehicle reference point was either the right front or right rear wheel (driver's perspective).

Vehicle Lateral Placement: the distance from the centre-line to the vehicle reference point (positive if the reference point was on the side of the road designated for the vehicle, i.e. positive if no centre-line encroachment). The lateral placement was equal to the vehicle lateral displacement if the vehicle measurement point was the vehicle reference point.

Wheel Span: the wheel span was the wheel to wheel width (outer face to outer face). If the vehicle reference point was the right front wheel, then the wheel span was the front wheel-to-wheel width; if the vehicle reference point was the right rear wheel, then the wheel span was the rear wheel-to-wheel width.

The transformation of the extracted data involved transforming the video frame counts into speed values, and where necessary, lateral displacement to lateral placement. The transformation of lateral displacement was only necessary if the vehicle measurement point was different from the vehicle reference point, the former being the left wheel of the vehicle in some instances. In this case, the lateral placement equals the lateral displacement less the wheel span. The lateral placement in the vicinity of the mid-point of the curve was then used to derive the wheel path radius at the curve mid-point.

The speed at each grid was computed from the frame count using the equation:

$$V = (90S)/N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

where

V = speed at grid n, in km/h

S = spacing between grid (n-1) and grid (n+1) i.e. 2 x spacing between control sections, in metres.

N = number of video frames between grid (n-1) and grid (n+1), which was also the sum of the frame counts for grids n and (n+1). (Note that the frame count at grid n = the number of frames between grid (n-1) and grid n).

The definition of N in equation (2.1) implies that rolling averages of the frame counts were used in the computation of speed values.

The wheel path radius at the mid-point of the curve was derived as shown below:

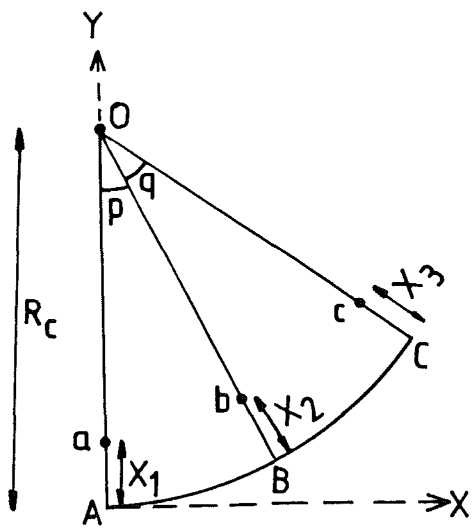

Figure 2.4 Wheel Path Radius At the Circular Arc

AB & BC	=	arc lengths between adjacent control sections, measured along centre-line.
a,b,c	=	vehicle reference point positions at control sections.
X_1, X_2, X_3	=	displacement of vehicle reference point from centre-line.
R_c	=	radius of centre-line
p & q	=	angles subtended by arcs AB & BC, respectively

Using basic trigonometry, it can be shown that the co-ordinates of a, b and c with respect to A are;

$$a = (X_a, Y_a) = (0, X_1)$$

$$b = (X_b, Y_b) = (R_c-X_2)\sin p, (R_c-(R_c-X_2)\cos p)$$

$$c = (X_c, Y_c) = (R_c-X_3)\sin(p+q), (R_c-(R_c-X_3)\cos(p+q))$$

The co-ordinates of a, b, c, were then used to calculate the circumscribed radius for the triangle formed by the 3 points a, b, c. This circumscribed radius was taken to represent the wheel path radius at point b. The circumscribed radius R is given by the equation :

$$R = (a'b'c')/(4A') \quad \text{......................} (2.2)$$

where a', b' and c' are the lengths of the sides of the triangle abc facing corners a, b and c respectively and A' is the area of triangle abc.

The sideway force coefficient, f, was computed using equation (1.1), restated here as

$$e + f = V^2/(gR) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.3)$$

where e, f, V, R are the superelevation, sideway force coefficient, speed and wheel path radius, respectively.

2.4.2 Level of Accuracy

The errors in the estimation of speed and lateral placement values are presented below. The error bounds give an indication of accuracy of the data, which would be useful in the comparison of different methods of data collection. The accuracy of the data is also used to determine whether higher order analysis (e.g. analysis of acceleration from frame counts) is warranted.

2.4.2.1 Accuracy of Speed Values

Equation (2.1) shows that errors in the computation of speed can arise from inaccuracy in the distance between the control sections (variable S) and inaccuracy in the frame count (variable N).

There were two sources of error in the variable S.

(a) The control sections may not have been exactly at S/2 units apart at the centre-line.

During the setting out, a measuring wheel was rolled along the centre-line to mark the control sections at every S/2 units apart. It was apparent that measurement errors arose mainly from failure to follow a path identical to the centre-line. The difficulty in this respect was compounded by the fact that the centre-line itself was represented by intermittent white strips 3 m x 100 mm with 7 m gaps. It was estimated that the error (for S at 20 m) was of the order of 10 cm (or +/- 0.5%). The error in the measuring wheel was less that 4 cm (+/- 0.2%) for S = 20 m, based on a calibration against a measuring tape on a smooth surface. A measuring wheel was considered more appropriate for setting out because it was possible to follow the contour of the road surface and it was capable of being operated by one person alone.

(b) The distance between the control sections was referenced at the centre-line. This means that the distance between the control sections on the inside of the centre-line was less than S while that on the outside was more than S. For example, for a radius of curvature of 150 m, a lane width of 3 m and S equal to 20 m at the centre-line, the distance between the respective control sections on the inside edge-line was 19.6 m while that on the outside edge-line was 20.4 m (a difference of +/- 2%). The actual distance travelled between the sections was very much influenced by the vehicle lateral displacement from the centre-line as well as the path radius. It was therefore not practical to identify precise error bounds. In general, the greater the centre-line radius of curvature, the smaller was the error in the distance S; the greater the vehicle displacement from the centre-line, the greater was the error in the distance S. For vehicles in the inside lane, the actual distance between control sections was less than S, while for vehicles in the outside lane, the actual distance was greater than S.

The sources of errors in the variable N (i.e. inaccuracy in the determination of the video frame count) were two-fold.

(a) Imprecision in the construction of grid lines. The errors introduced by poor construction of grid lines was difficult to quantify. The only check carried out was to compare frame counts between adjacent pairs of grids, to ensure that the difference in frame counts should be within the limits consistent with feasible changes in speed.

(b) Difficulty in pin-pointing exactly when the vehicle reference wheel was on the grid, as a result of the discrete recording format (recording of vehicles at regular time intervals rather than at points of interest i.e. control sections) and the type of perspectives. Highly elevated perspectives improved the accuracy of determining the wheel-on-grid position since the spacing of grids increased with an increase in the angle of elevation. For this reason, accuracy was higher for near grids than distant grids. Distant grids were also more seriously affected by the resolution of the video equipment. The discrete recording format of 25 rames per second implied a 0.04 s time interval between frames, which is equivalent to a picture at every metre interval for a vehicle moving at 90 km/h (25 m/s). The wheel-on-grid position was estimated to the nearest half frame (+/- 0.01 s at each of the near grids and to the nearest frame (+/- 0.02 s) at the far grids. About 20% of the grids were considered as distant grids. Data were extracted sequentially from the first grid (at entry) to the last grid (at departure), where the terminating frame count at any grid n marked the beginning of the frame count for grid (n+1),which was equivalent to cumulative frame counting. The errors at any particular grid were thus complementary, and therefore the errors in the number of frames over any number of sequential grids were the sum of the errors at the first and last grids since the errors in the in-between grids cancelled each other out. There was a certain amount of conscious compensation in estimating the number of frames between a pair of grids in the sense that if there was under-(or over-) estimating in the beginning frame then there was a tendency to compensate by over-(or under-) estimating the terminating frame, where appropriate. Hence the errors in the beginning frame and and terminating frame were not always independent, with smaller errors being more likely as a result.

The error bounds for N can be worked out as follows:

Let N1 be the starting frame at grid (n-1)
Let N2 be the terminating frame at grid (n+1)
Number of frames between grids (n-1)and (n+1) = (N2-N1)

Assuming the grids were distant grids, then the maximum errors in N1 and N2 were +/- 0.5 frame.

If the errors were normally distributed, with a mean of zero, then the likely maximum error is about two standard deviations (since the 95 percent error bounds are approximately +/- two standard deviations). Hence, the standard deviation of N1 and N2 is +/- 0.25 frame, approximately.

Assuming the errors in N1, N2 were independent (a conservative assumption, since compensation during data extraction would give smaller errors), then

variance (N2-N1)= variance (N1) + variance (N2)

= 0.125 frame, and

std. dev. (N2-N1) = 0.35 frame

= standard error (SE) of (N2-N1)

Note that for a single (N2-N1), the standard error SE is the standard deviation of (N2-N1). The probable error is defined as the value E such that the probability of an error greater than E is 1/2 (Bannister and Raymond 1978).

Probable error E = 0.67 x SE

= 0.23 frame

Likely max. error = 2 x Std. dev.

= 0.70 frame

These computations are for distant grids. For near grids, the probable and maximum errors for (N2-N1) would be 0.15 and 0.35 frames respectively. For a vehicle travelling at 90 km/h over a distance S = 20 m (i.e. (N2-N1) = 20 frames), the maximum error bounds are +/-3.5% and +/-1.75% for distant and near grids respectively.

The errors in the estimation of the speed values arise from the interplay of various factors, and it is impractical to obtain an exact error bound. It is estimated, based on a consideration of the various sources of errors described previously, that the magnitude of the error should be within +/- 10% for the 'worst' case and about +/- 5% overall.

2.4.2.2 <u>Accuracy of Lateral Placement Values</u>

The errors in the estimation of lateral displacement were influenced mainly by the scale of the grids, and to a lesser extent the calibration of the grid. The grids were graduated to a smallest division of 10 cm. For front-on perspectives, the lateral displacement could be estimated to the nearest 5 cm (i.e to within +/- 2.5 cm) at most of the grids. However, in about 10% of the grids where the scale was less than 1:10 (the distant grids) and the deviation from front-on was greater than 15 degrees, the lateral displacement was estimated to the nearest smallest division (i.e.to within +/- 5 cm). The main difficulty in such instances was the poor resolution of the video equipment, resulting in less than desirable picture definition. Also, because the measurement points were not always on the grids as a result of the discrete recording format of 25 frames per second, a front-on perspective would result in more accurate estimation of lateral displacement.

The errors from the calibration of the grids could arise from poor graduation (such as using a wrong scaling factor) and unequal division, as well as the grids not being horizontal. The quality of grid graduation was easily checked by visual inspection. The grids were graduated with equal divisions on the assumption that a horizontal line is a line of constant scale. Hence, front-on perspectives were essential to the method of graduation. (Field trails showed that the video equipment could not provide accurate graduation by means of filming a graduated scale placed across each of the grids). A grid line that was not horizontal, after taking account of the superelevation of the road, implied unequal scale across the grid, and thus would complicate the graduation procedure. In the field work carried out, all the grids sections were reasonably 'horizontal'. The errors resulting from the calibration of the grids were considered to be much less than reading errors during data extraction.

The lateral displacement values had to be converted to lateral placement in some cases, by subtracting the vehicle wheel span. Wheel span values were extracted at the foreground grid where the scale was at its largest and there was also a conscious compensation to reduce erros. Wheel span values were likely to have a maximum error of +/- 3 cm. Using the line of argument as presented for estimating the errors for speed values, the maximum error in the conversion of lateral displacement to lateral placement at the distant grids (+/- 5 cm) was approximately 6 cm, and that at the near grids (+/- 2.5 cm) was less than 4 cm. The conversion from lateral displacement to lateral placement was required only for the outside curves at the Leithfield study site.

2.4.2.3 Accuracy of Path Radius and Sideway Force Coefficient

The error bounds for the wheel path radius and sideway force coefficient were considered too complicated to warrant detailed analysis. The wheel path radius and sideway force coefficient all showed sensible values. Given that the errors in speed and lateral placement were likely to be randomly distributed, it would not be unreasonable to assume a random distribution in the errors of the wheel path radius and sideway force coefficient.

2.4.3 Analysis of Reduced Data

The reduced data were analysed to provide information about various aspects of driver behaviour along the curve as well as at particular points of the curve. The analysis was performed using the SAS statistical package. Statistical tests were included where appropriate.

2.4.3.1 <u>Driver Behaviour Along the Curves</u>

The variables that were studied in relation to driver behaviour along the curve were the speed, lateral placement, centrality index (to be defined later) and pattern of encroachment upon the delineation lines. The results were presented as profile plots.

The speed variable was analysed, to estimate the mean of the vehicle speeds and the 95% confidence interval, at points along the curve. The acceleration and deceleration rates of individual vehicles were not estimated, because the data extraction procedures (based on frame counts for travel time) had resulted in the speed value becoming a discrete variable rather than a continuous variable. Calculation of acceleration and deceleration would have required the squaring of the speed values, resulting in a profile with sharp rises and dips. A smoothing function would have been needed to smooth the sharp rises and dips, and such a procedure was not employed, since acceleration (or deceleration) estimates would entail using the differences in similar speeds, so that errors in the acceleration (deceleration) would be very much greater than the errors in the speed estimates.

Lateral placement values provide a straightforward indication of the pattern of lane usage (i.e. variations in vehicle lateral displacement from the centre-line). Again profiles were obtained, showing the mean lateral placement (and the 95% confidence interval) at points along the curves.

A measure to describe the positioning of the vehicle between two reference boundaries (e.g. lane delineation lines) was defined, to provide information on the centrality of subject vehicles. In formulating a centrality measure, the following criteria were considered:

(a) the measure should reflect displacement from two reference boundaries.

(b) the measure sould incorporate vehicle width (or wheel span) directly or indirectly.

(c) the measure should preferably be dimensionless, so that computation can be done in any consistent set of units, and comparison can be made at different road cross-sections.

A non-dimensional measure similar to the centrality index as used by Stimpson et al (1977) was defined to describe the centrality of subject vehicles at a control section as follows :

$$CI = (X1 - X2)/TW \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.4)$$

where

CI = centrality index

$X1 =$ distance of outer face of right wheel to the right boundary (driver's perspective)

$X2 =$ distance of outer face of left wheel to the left boundary (driver's perspective)

$TW =$ width between the right and left reference boundaries

For 2-lane, 2-way roads, which are the cases at the study sites, the logical choice for the right boundary is the centre-line, while the left boundary can be either the edge-line or the edge-of-seal on the side of the road designated for the vehicle. (For multi-lane carriageways, the boundaries can be lane delineation lines or other appropriate combinations). With the centre-line as the right boundary, the parameter X1 is also the lateral placement of subject vehicles, within the context of the definition of lateral placement as discussed above. By incorporating the vehicle wheel span VW in the centrality index equation, equation (2.4) can be rewritten as

$$CI = (2 * X1 + VW - TW)/TW \qquad (2.5)$$

Using equation (2.5), the centrality index can be computed from vehicle lateral placement and wheel span at a specified cross-sectional width TW. Where the right front wheel was the vehicle reference point, VW was the front wheel span, and where the right rear wheel was the vehicle reference point, VW was the rear wheel span. The variation of centrality index at a control section is illustrated in Figure 2.5.

Figure 2.5 shows that

(a) CI = -1 implies the vehicle is centrally placed above the right boundary (the centre-line).

(b) CI = 0 implies the vehicle is centrally placed between the right and the left boundaries.

(c) CI = +1 implies the vehicle is centrally placed above the left boundary (edge-line or edge-of-seal).

The above relationship holds true for all vehicles.

The value of the centrality index is affected by the wheel span; all other things being equal, one gets a larger CI for a large wheel span and a smaller CI for a small wheel span. Thus, two vehicles with different wheel spans but identical lateral placement will give different values of CI. The mean centrality index with 95% confidence interval was computed for each of the study curves.

The encroachment pattern on the road delineation lines was expressed as the proportion of the vehicles for which the vehicle reference point

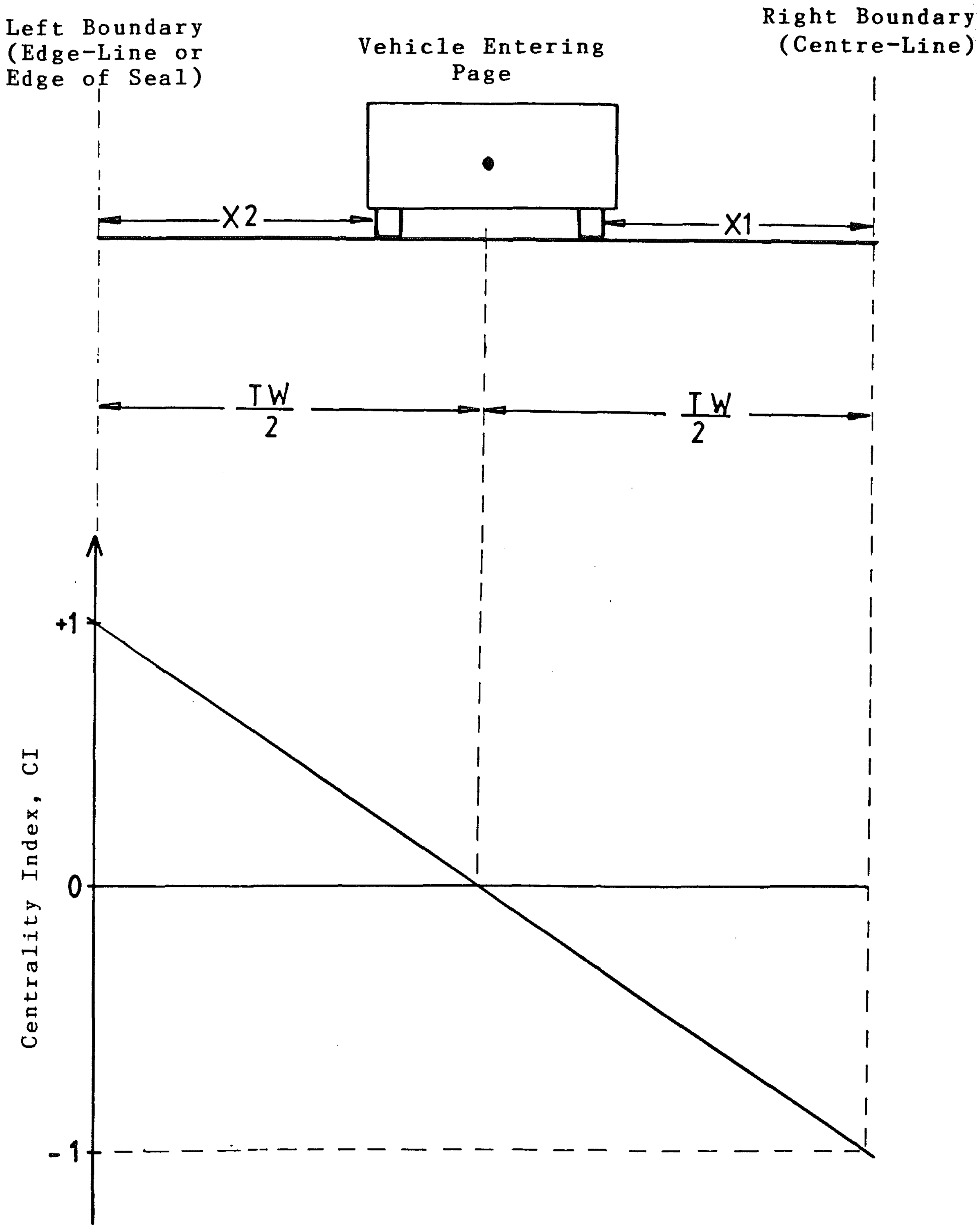

Fig. 2.5 <u>Centrality Index of Vehicle Centered between Left and Right Boundary</u>

encroached upon (or went beyond) the centre-line, and the proportion for which the outer face on the vehicle left wheel encroached upon or went beyond the left edge-line (driver's perspective). The proportions were shown (as percentages) at each of the control sections.

2.4.3.2 Driver Behaviour at Particular Points on Curves

The variables that were studied at the mid-point of the curve included speed, lateral placement, path radius and required side way force coefficient. The results were presented as cumulative frequency plots. (Speed values were also studied at the curve approach and at the curve entry in some cases).

The curve mid-points were chosen as the main point of analysis for the following reasons.

(a) This was the point with the highest level of accuracy for all the data. This was particularly true for the vehicle wheel path radius which was referenced to the centre-line radius. The centre-line radius was estimated most accurately at the curve mid-point by virtue of it having the minimum radius at this point and therefore it was able to be measured with greater accuracy than at any other points on the curve. The path radius was most accurate at the curve mid-point by virtue of its base reference (the centre-line radius) being more accurate at the mid-point, as well as the greater accuracy in the reduced placement data in the vicinity of the curve mid-point (as a result of a better camera position giving a larger vehicle image, horizontal grid sections, and a full frontal view of vehicles at the curve mid-point).

(b) The curve centre-line radius was constant for the after-study curves, and relatively constant for the before-study curves, at the curve mid-point.

(c) The curve mid-point was a point of symmetry and therefore the influence of opposing vehicular flow was studied by conveniently applying a vicinity length extending equal distances in both directions. The vicinity length was used for determining whether the behaviour of a subject vehicle was affected by an opposing vehicle.

(d) The mid-points of curves have traditionally been the regions of greatest interest.

CHAPTER III

3.1 STUDY SITE

The study described in this chapter involved a before-study on a curve prior to curve improvement (the BS curve) and an after-study curve subsequent to curve improvement (the AS curve). The BS and AS curves have a common apex point. The site is on State Highway SH1 at reference point RP 351/5.7 in Road District RD14 (Figure 3.1). The study site is also referred to as "the Foremans Road curve". The curve improvement was carried out in conjunction with the shape-correction of part of the adjoining tangent linking Templeton.

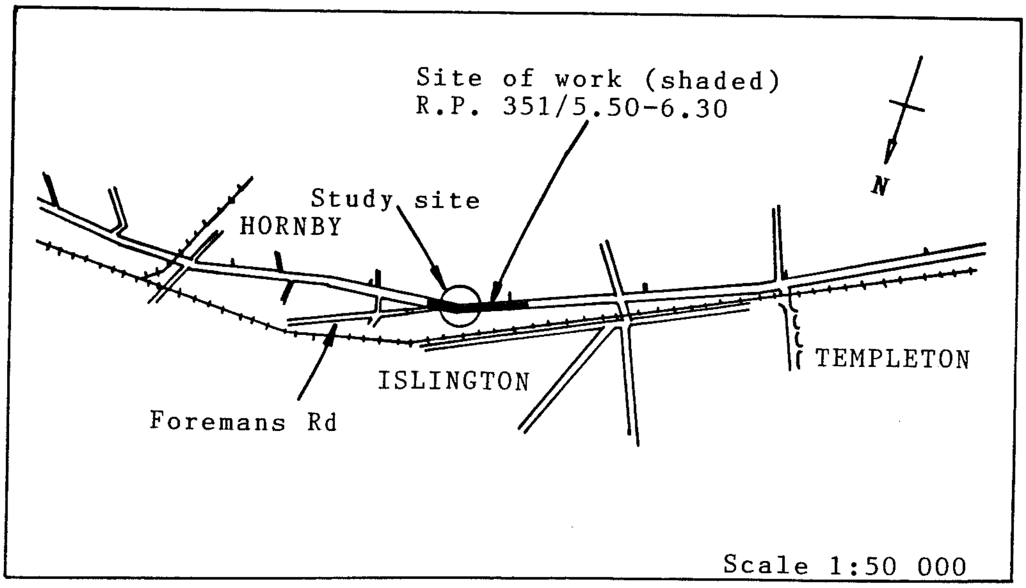

Fig. 3.1 Locality Plan of Study Site

The site is on flat terrain, in semi-rural surroundings, with land adjacent to the road being used for pastures and cereal cultivation. There are a couple of buildings located on the outside of the curve near to the curve mid-point with access through Foremans Road only since Foremans Road is closed at the western end. There are power and telegraph poles on both sides of SH1.

The study site is on a stretch of state highway with open road speed limit i.e. maximum speed of 100 km/h. However there are restricted speed zones of 50 km/h and 70 km/h on both approaches to the study site (Figure 3.2). The 70 km/h speed zones are 600 metres from the curve mid-point in both directions. The BS curve had an estimated design speed of 65 km/h while the AS curve design speed is 90 km/h. There was no advisory speed sign at either curve.

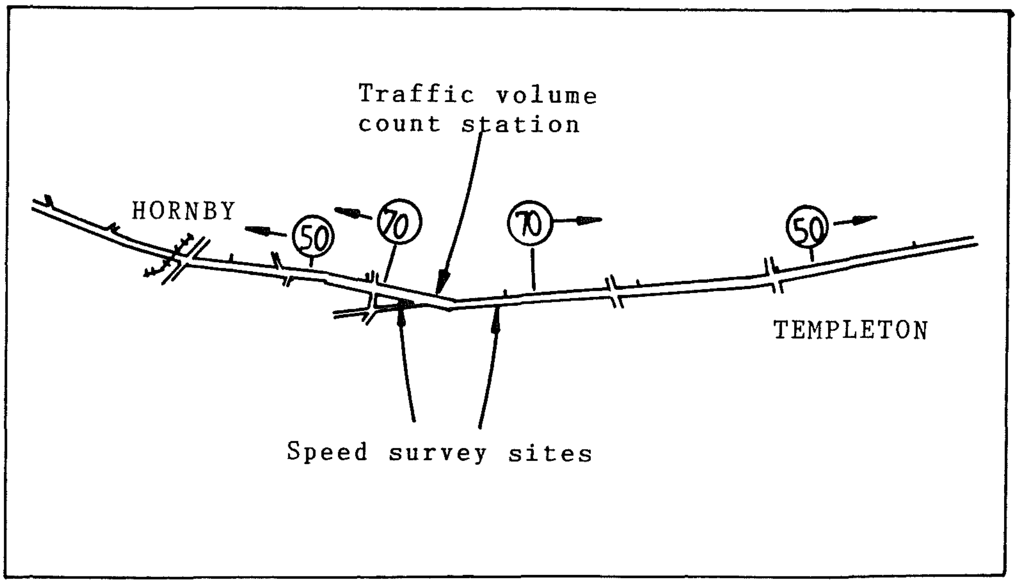

Fig. 3.2 <u>Speed Zones, Speed Survey Sites and Traffic Volume Count Station</u>

Speed surveys using closely-spaced pneumatic tubes were carried out at 300 metres from the curve mid-point on both approaches for the BS as well as the AS curves (Figure 3.2). The speed values within the curves were obtained from recorded video data. A traffic volume count station operated by Ministry of Works and Development is sited within the study area, as shown in Figure 3.2.

The layout of the BS and AS curves are as shown in the superimposed plots of Figure 3.3. The tangent-spiral junctions and the curve mid-point of the BS curve are marked as ST′, TS′ and MP′ respectively. The tangent-spiral, spiral-circular and curve mid-point of the AS curve are similarly marked (minus the prime symbol). The positions of roadside appurtenances (sight-rail, chevron board and guard-rails) are also indicated on the plans.

The curve data for the BS and AS curves are as presented in Table 3.1.

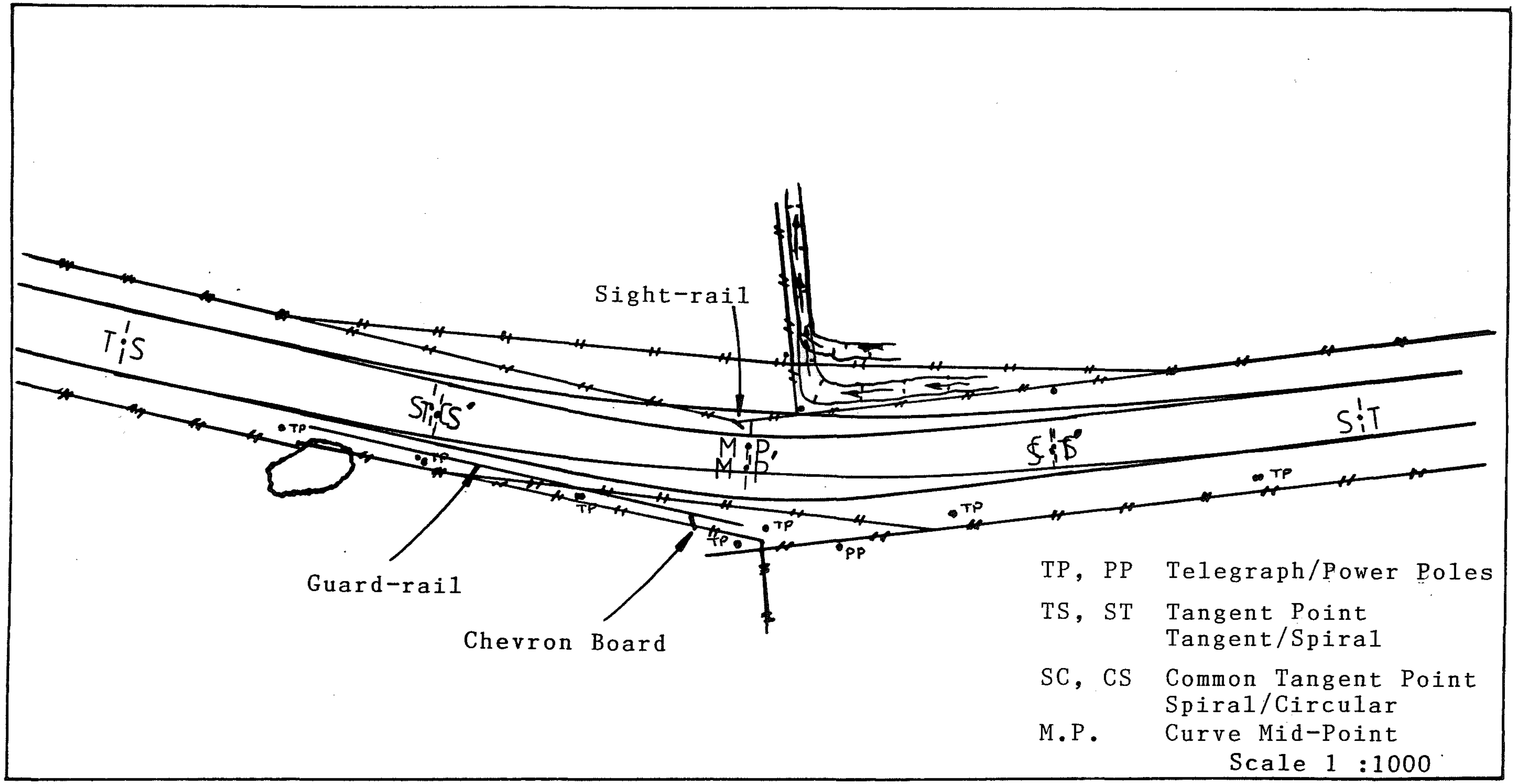

Figure 3.3 Before Study Curve (in Transparency) and After Study Curve

	Before	**After**
Design speed value (km/h)	65	90
Centre-line radius (m)	150	450
Super elevation (%)	+6.2	+4.4
Sideway force coefficient, SFC (at above speed value)	0.16	0.10
Curve length (m)	100 total	200 total (Circular arc 100 Spiral 2x50)
Sight distance restriction	no stopping sight distance restriction	
Skid resistance (BPN) at curve mid-point region	78 (Dry) 57 (Wet)	98 (Dry) 75 (Wet)
Texture depth (mm)	1.51	2.55
Surfacing:		
Chip grade	2	3
Binder	180/200	Soft residue asphaltic cutback
Treatment	Reseal	New
Date of Completion	1979	1986
AADT	7425 (NRB/AADT 1983)	
Average Daily Traffic	9063 (Counts from 31/1/85 at Station 6/1S/28)	

Table 3.1 <u>Before-Study and After-Study Curve Data for Foremans Road Curve, at Curve Mid-Point Region</u>

The lane and sealed roadway widths over the length of the road being studied are as shown in Figure 3.4, where the widths on the outside curve are plotted on a positive scale and those on the inside curve are plotted on a negative scale. The horizontal arrows on the plots indicate the direction of traffic flow relative to the abscissa. The profiles in Figure 3.4 show that there was relatively little change in the lane width, while there were quite large changes in the sealed roadway widths.

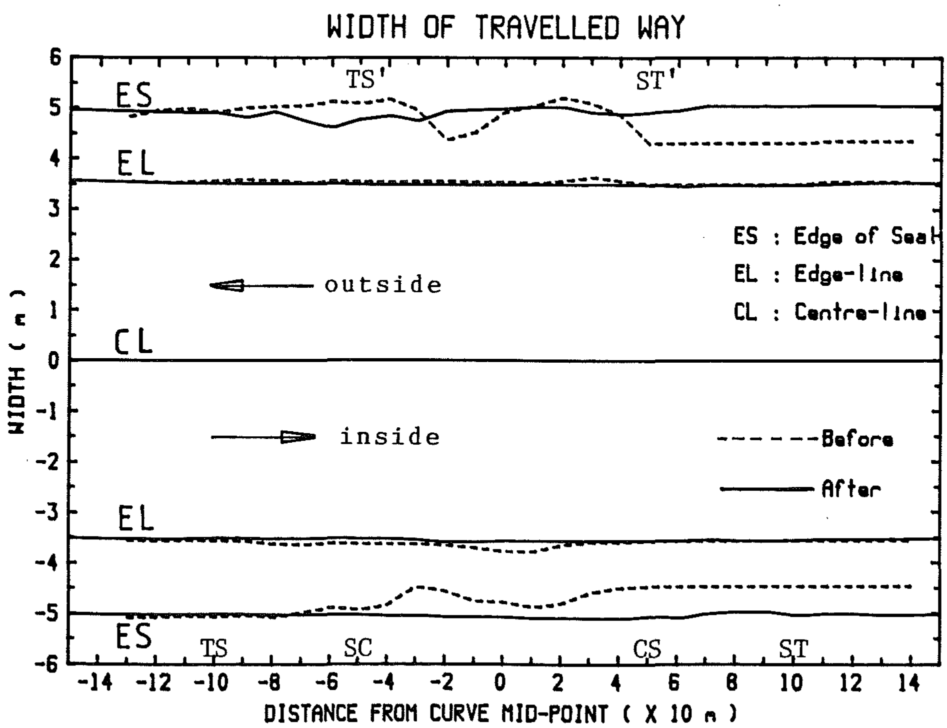

FIGURE 3.4

The mid-point of the curve (at the centre-line) is used as the origin for longitudinal measurement. The direction of distance increment was chosen to be the same as vehicle flow direction on the inside curve. This is equivalent to positive distance from the curve mid-point towards Templeton and negative distance from the curve mid-point towards Hornby, as shown in Figure 3.1.

The centre-line at each control section, interpolated if necessary, is used as the origin for lateral placement at that control section. Lateral placements of subject vehicles were given positive values if the "reference points" were within the travelled lane (i.e. a positive value if there was no centre-line encroachment). The vehicle "reference points" were the outer face of the right front wheel at ground level. The term 'inside' (or 'outside') was used to denote that side of the road nearer to (or further from) the centre of the curve. Superelevation values were given positive values if the road cross-section sloped towards the centre of the curve, and negative values if the cross-section sloped away from the centre of the curve.

3.2 DRIVER BEHAVIOUR DATA COLLECTION

3.2.1 Period of Data Collection

Data were collected during day-light hours and in dry weather. The BS and AS curves could be grouped into four cases with the periods of data collection as shown in Table 3.2.

Case	Date/Day	Time
BS inside	5/2/86 (Wed.)	12.00 pm - 4.00 pm
BS outside	4/2/86 (Tue.)	12.00 pm - 4.15 pm
AS inside	10/12/86 (Wed.)	11.30 am - 3.00 pm
AS outside	11/12/86 (Thurs.)	11.30 am - 4.15 pm

Table 3.2 Periods of Data Collection

Traffic count data had indicated a similar flow pattern over everyday of the week. The hourly flow rate was also fairly constant between 10 am and 4 pm. The hours of data collection all fall within the weekday time period when the proportion of drinking drivers is very low (Bailey 1980).

The AS data collection was done 9 months after the completion of the reconstruction job. This allowed ample time for the 'novelty' effect of the 'new' curve to wear off.

3.2.2 Sample Sizes

The data collection exercise yielded four data sets, one for each case. Within each data set, the data were further disaggregated into those for vehicles with opposing vehicular flow (WV) and without opposing vehicular flow (WOV) within "the vicinity" (as defined below). The sample size for each case was as shown in Table 3.3.

Case	WV	WOV	Total
BS inside	104	102	206
BS outside	76	108	184
AS inside	97	50	147
AS outside	103	43	146

Table 3.3 Sample Sizes

The vicinity boundary points for WV vs WOV were chosen to be the curve tangent spiral junctions (i.e. vicinity length = curve length). This had the effect of the AS curve having a vicinity length double that of the BS curve's. This explains the lower proportion of WOV's for the AS curve.

Spatial boundary points rather than time intervals were used for delimiting the vicinity because of the simplicity in data reduction for spatial limits. For time interval-based limits, the variations in the speed of the subject vehicles and the opposing vehicles over the length of the curve implied that the physical boundary points of the vicinity were not fixed, thereby necessitating an iterative data reduction process. The time interval-based limits also could not easily handle the case where the subject vehicle met a platoon of vehicles.

In choosing the tangent spiral junctions as the boundary points, it was assumed that meeting other vehicles within the length of the curve would have a significant effect on the behaviour of subject vehicles. This was considered realistic, especially for the case of driver behaviour at the mid-point of the curve. The effect of variation in the length of the vicinity on driver behaviour was not investigated and was beyond the scope of this study.

The reduced data contained, for each subject vehicle, the speed and lateral placement values at each control section, as well as the vehicle front wheel span and whether there was or was not opposing vehicular flow in the vicinity. Data were restricted to vehicles with a width between 1.2 m and 1.8 m (i.e. heavy vehicles were not included).

3.3 ANALYSIS OF DATA AND PRESENTATION OF RESULTS

3.3.1 Data Analysis

Data analysis was done using the SAS statistical analysis package. Plots were generated using the NCAR Graphical Package and were plotted on an HP plotter.

Analysis was performed to obtain "profiles" showing variation in driver behaviour characteristics along the curves as well as cumulative frequency (cdf) plots for those characteristics at particular points on the curves. The curve mid-point was chosen for detailed analysis of driver behaviour for all the cases.

3.3.2 Choice of Mid-Point as Point of Analysis

The curve mid-points were chosen as the main point of analysis for the following reasons.

(a) This was the point with the highest level of accuracy for all the data. This was particularly true for the vehicle wheel path radius which was referenced to the centre-line radius. The estimate of centre-line radius was most accurate at the curve mid-point by virtue of it having the minimum radius at this point and therefore being able to be measured with greater accuracy than at any other points on the curve. The path radius was most accurate at the curve mid-point by virtue of its base reference (the centre-line radius) being more accurate at the mid-point, as well as the greater accuracy in the reduced placement data in the vicinity of vicinity of the curve mid-point (as a result of a better camera position giving a larger vehicle image, horizontal sections, and a full frontal view of vehicles at the curve mid-point).

(b) The curve centre-line radius was constant for the AS curve, and relatively constant for the BS curve, in the region of the curve mid-point.

(c) The curve mid-point is a point of symmetry and therefore the influence of opposing vehicular flow can be studied by conveniently applying a vicinity length extending equal distances in both directions.

(d) The mid-points of curves have traditionally been the regions of greatest interest.

3.3.3 Presentation of Results

Most of the results are presented as linear graphical plots. Symbols were not included at data points to facilitate clarity. Where the abscissa of plots were distances from the curve mid-point, data points were at every 10-metre interval along the curve (for both BS and AS curves). The results are presented as set of plots, e.g. mean speed profiles for BS/AS, inside/outside. For each set of plots, the same scale or the same interval of scale was used wherever possible for both abscissa and ordinate axes. Therefore both the values at various points and the slope of the graphs can be easily compared.

The direction of subject vehicle flow in the profile plots is indicated by the direction of the arrow. A right pointing arrow indicates going towards Templeton; likewise, a left pointing arrow implies the subject vehicle was going towards Hornby. The sample size used for analysis was total sample size for that case, unless otherwise specifically stated that WV or WOV sample sizes were used. The start and end of the BS curve (TS′, ST′), the start and end of the AS curve (TS, ST) and the start and end of the AS circular arc (SC, CS), as shown in Figure 3.3, were marked on the abscissa where appropriate.

3.4 BEHAVIOUR ALONG CURVES

3.4.1 Mean Speed Profiles

The mean speed profiles (with 95% confidence interval) for the four cases are shown in Figures 3.5-3.8.

3.4.1.1 Mean Speed Profiles : BS Curve

The profiles (Figure 3.5) show a fairly steady drop in mean speed from the points 120 m upstream of the mid-point (i.e. 70 m upstream from the start of the curve) showing that drivers had started reducing speed at quite a considerable distance away. The minimum mean speed for the inside curve was reached at one-third of the distance through the curve (i.e. before

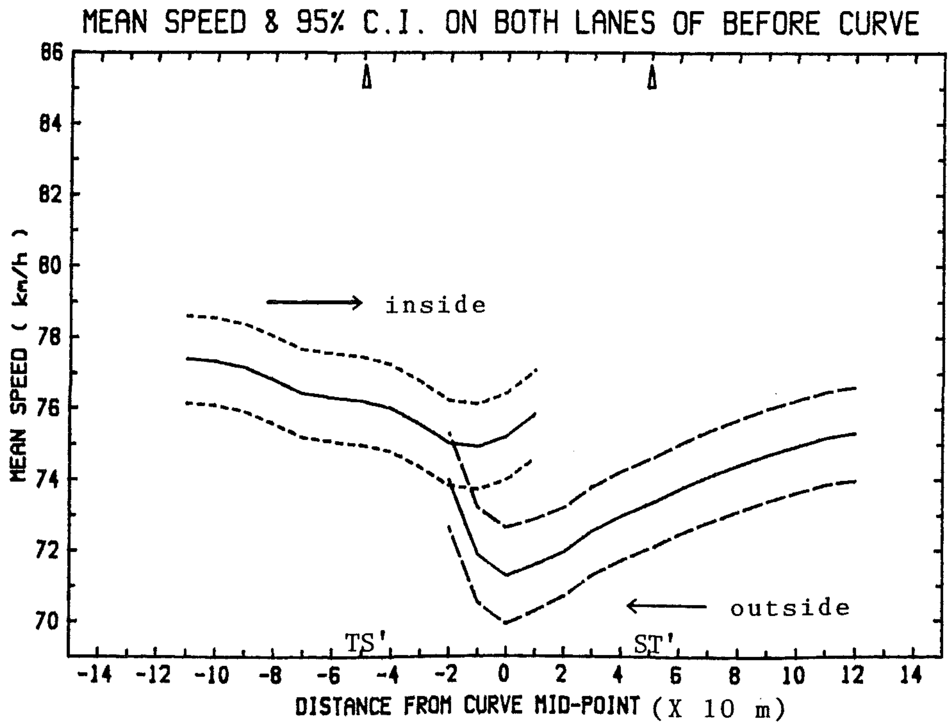

FIGURE 3.5

the mid-point); the drop of 2.48 km/h over the preceding 100 m was equivalent to a deceleration of 0.15 m/s/s. The minimum mean speed value for the outside curve occurred at the curve mid-point; there was a drop of 4.07 km/h over the preceding 120 m giving a deceleration of 0.19 m/s/s. In both cases, the rate of acceleration out of the curve exceeded the rate of deceleration.

The commencement of speed reduction from such a considerable distance from the curve entry indicates that the average drivers had perceived the curve ahead and had taken steps to prepare for curve entry. The fairly gradual but steady drop in speed in the curve approach suggests that there was little change in the drivers' perception of the level of difficulty of the curve ahead while progressing towards the curve. No conclusion is drawn regarding the continuing drop in speed right into the middle third of the curve. However, the profiles show that acceleration and deceleration were not mirror images of each other. There is a distinct point of inflexion for each profile, and the evidence is inconsistent with the standard design assumption of constant speed inside a curve. The greater acceleration following the point of minimum mean speed suggests the desired travel speed was greater than the perceived safe speed in curve; on this basis, the location of the inflexion points within the approach half of the curve suggests adequate speed control by the drivers, since it could be argued that poor speed control (such as entering the curve at too fast a speed) would have required a continuing speed reduction up to or beyond the curve mid-point.

The mean speed at 60 m before curve entry was not significantly different (at the 95 percent confidence level) between the inside and the outside curves. However, the deceleration for the outside curve was nearly 30 percent greater than for the inside curve. This shows that different speed control strategies were employed for the different sides (the inside and outside) of the same curve. This highlights the need to study the two halves (inside/outside) of the curve separately.

3.4.1.2 Mean Speed Profiles : AS Curve

A dip-flat-rise profile (Figure 3.6) was observed for the inside curve, with the flat region extending from 20 m into the curve to 20 m past the curve mid-point (i.e. a distance of 100 m or 50 percent of curve length). The reduction in mean speed in the dip was 2.67 km/h over a distance of 60 m, giving a deceleration of 0.27 m/s/s, while the rise was equivalent to 3.82 km/h over a 60 m length with acceleration equal to 0.39 m/s/s.

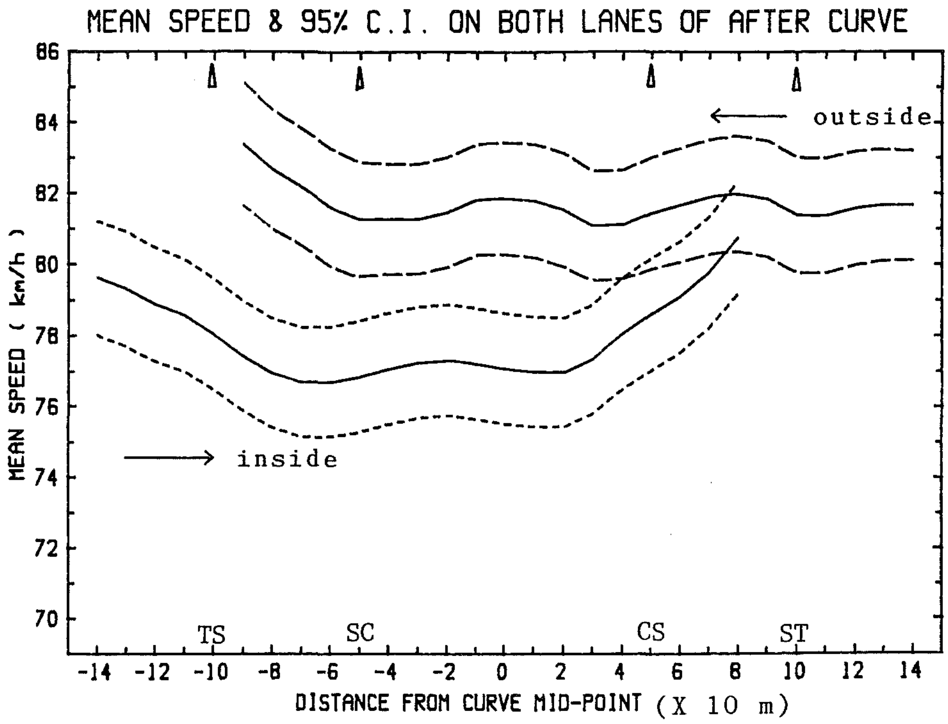

FIGURE 3.6

The mean speed for the outside curve exhibits a fairly level profile with no distinct region of speed reduction in the curve. There was a noticeable speed increase of 2.13 km/h, with acceleration equal to 0.29 m/s/s, at the departure spiral region.

The dip-flat-rise mean speed profile of the inside curve shows that the average drivers decelerated to a point half-way into the spiral, maintained a fairly uniform speed over the remainder of the spiral and through 3/4 of the circular arc, to be followed by a strong acceleration. The deceleration pattern shows that the average drivers perceived the need to reduce speed quite significantly; however the commencement of strong acceleration before the end of the circular arc suggests the desired travel speed is greater than the perceived safe speeed, since slower deceleration than acceleration indicates a reluctance to decrease speed and a desire to increase speed as soon as possible.

The profile for the outside of the curve is significant for its absence of a distinct deceleration zone. Within the limits of the observation zone, it could be assumed that the average drivers had not perceived the need to slow down from beyond 40 m prior to curve entry and right through the circular arc. The fairly strong acceleration at both the departure spiral suggests drivers' confidence in negotiating the remainder of the curve.

3.4.1.3 <u>Changes in Mean Speed Profiles : Before/After</u>

With reference to Figure 3.7, the mean speed profiles for the inside curves do not show statistically significant differences (at the 95% confidence level).

The mean speed profiles in Figure 3.8 show very large speed differences between the before and the after outside curves. There are also large differences in the steepness of the slope indicating significant differences in the acceleration/deceleration patterns.

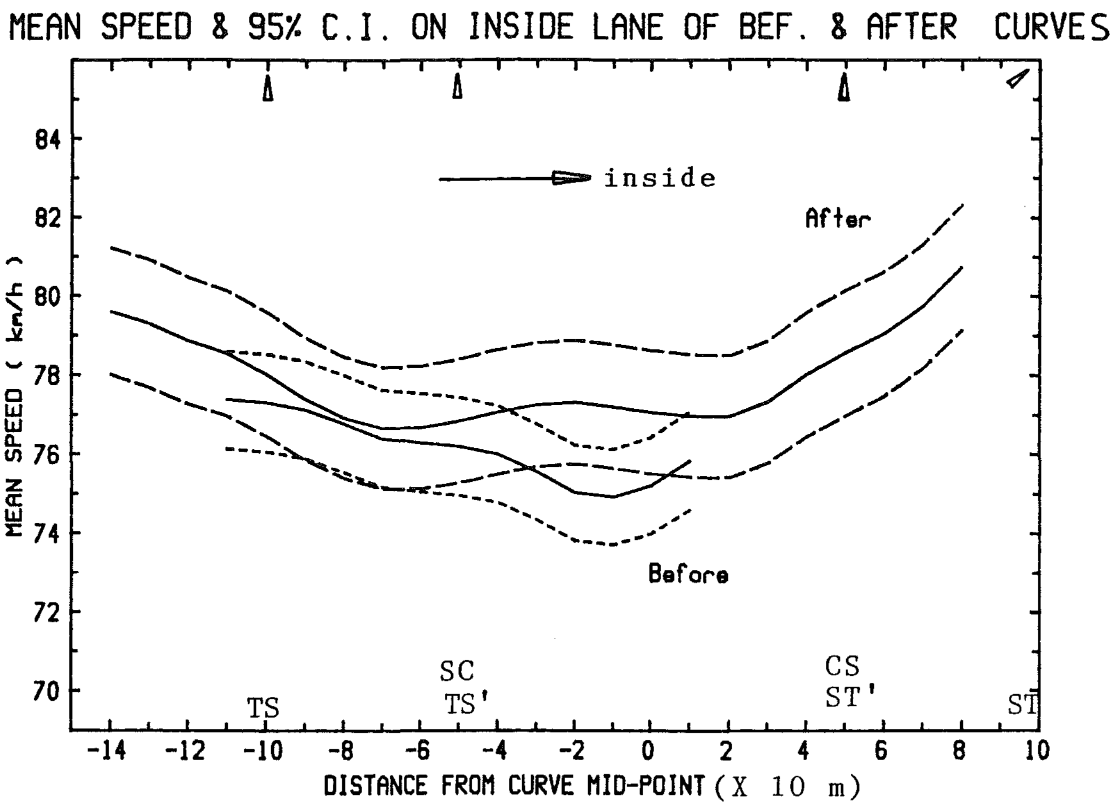

FIGURE 3.7

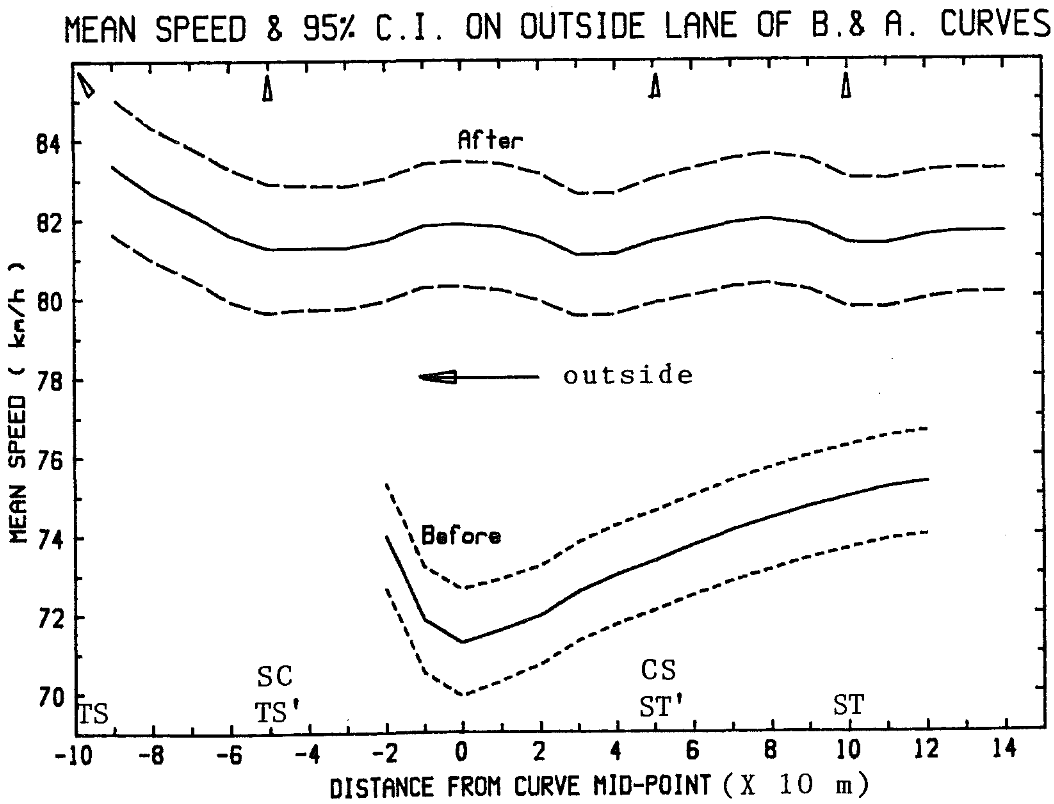

FIGURE 3.8

3.4.2 Cumulative Speed Distributions

The cumulative speed distribution (cdf) for each of the four cases are shown in Figures 3.9a-d. The plots have the same scales.

The cdf plots all show an 'S' profile with fairly long tails. The 'S' profiles indicate speed conforming to a normal distribution, the long tails showing variation over a wide range of speed values. Speed cdf's are shown for the curve mid-point, for the curve entry and 40 m from curve entry. Comparing the profiles it is apparent that there are relatively large differences over a wide range of speed values between the speed at the three points for the outside BS curve and inside AS curve.

The design speed for the BS and AS curves were 65 km/h and 90 km/h respectively. From Figures 3.9a-d, the percentages exceeding these design speed values at curve entry and curve mid-point are found to be as shown in Table 3.4.

Case	Entry (%)	Mid-Point (%)
Inside BS	90	88
Outside BS	80	68
Inside AS	11	8
Outside AS	15	15

Table 3.4 Proportions Exceeding Design Speed

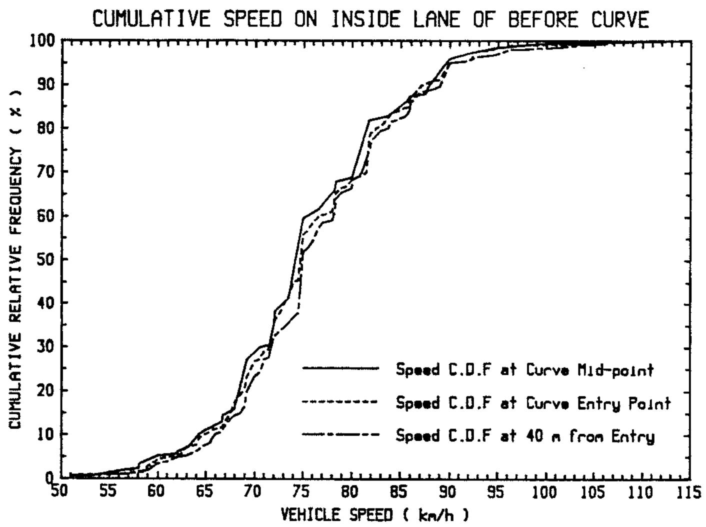

FIGURE 3.9a

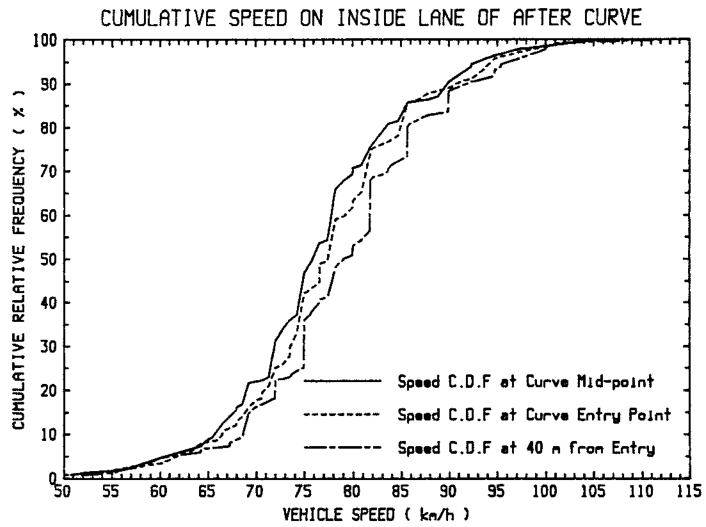

FIGURE 3.9b

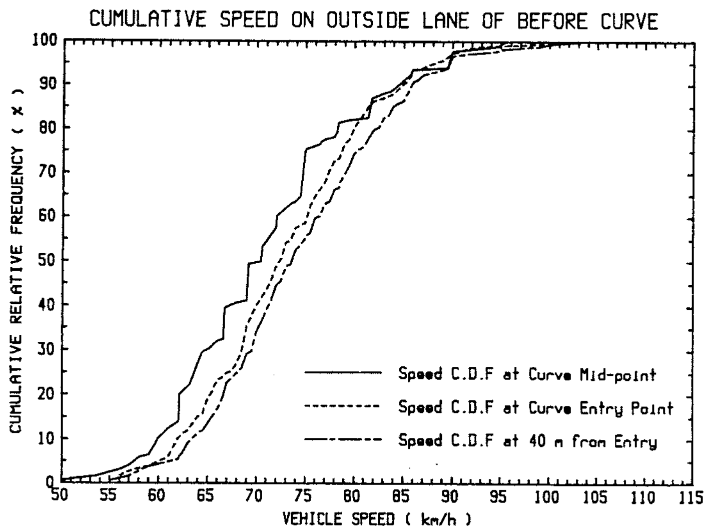

FIGURE 3.9c

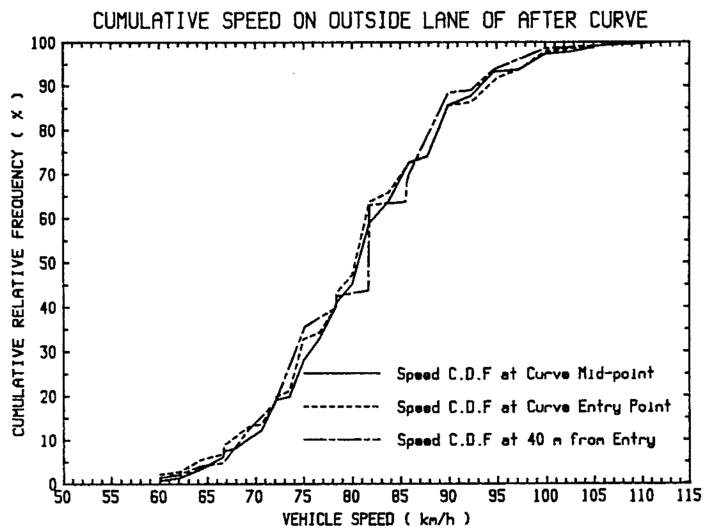

FIGURE 3.9d

In terms of the percentage exceeding the design speed, the AS curve shows a substantial improvement over the BS curve.

3.4.3 <u>Mean Lateral Placement</u>

The mean lateral placement (MLP) profiles are presented in the following sections. The MLP profiles are plotted on a positive scale for the outside curve and a negative scale for the inside curve. The centre-line is represented by the line of zero MLP.

3.4.3.1 <u>Mean Lateral Placement on Before-Study Curve</u>

The MLP profiles for the BS curve (Figure 3.10a) show distinct corner-cutting within the curve, as reflected by the deep troughs in the profiles. Strong lateral shifts commenced at approximately 10m before curve entry and reached extreme values at the mid-point of the curve, to be followed by strong recovery. There is no region of the profiles within the curve for which the MLP is constant, implying that vehicle path radius is not equal to curve centre-line radius. The 95 percent confidence intervals (dashed lines) are fairly constant along the length of both profiles indicating constant variance in the MLP.

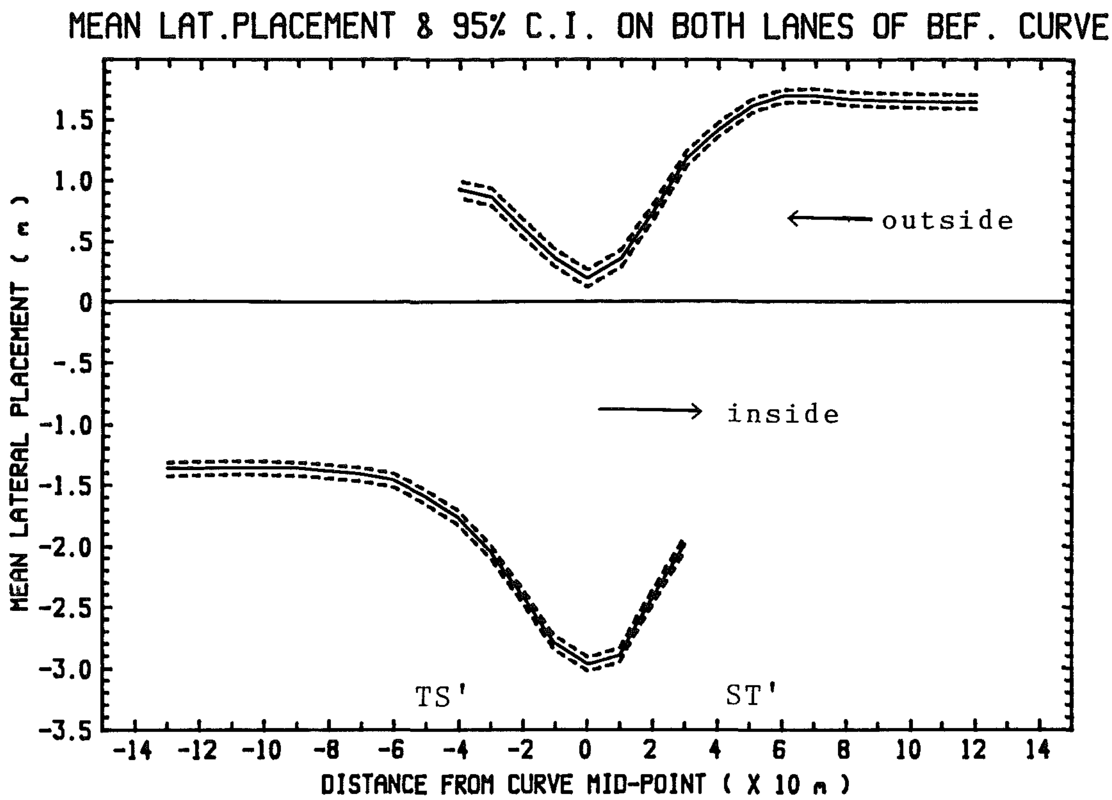

FIGURE 3.10a

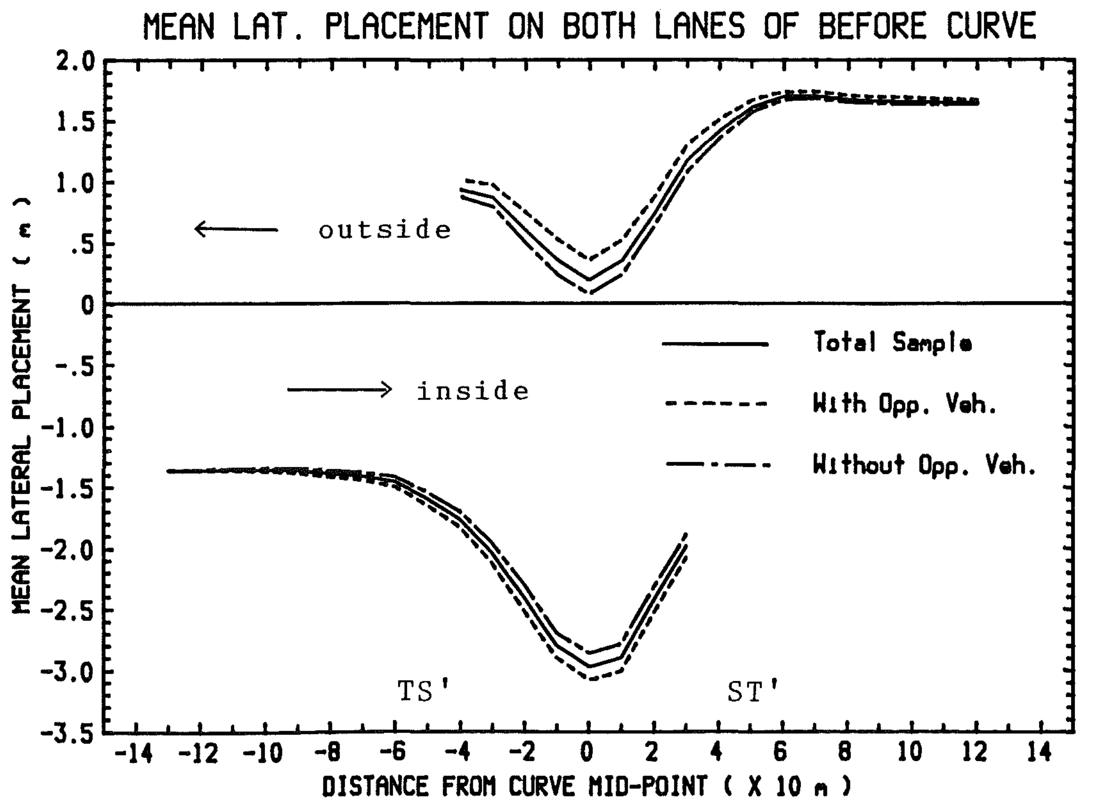

FIGURE 3.10b

Comparing the MLP profiles with roadway width, the MLP's do not seem to be influenced by the quite large variations in the roadway width (see Figure 3.4). There is also no apparent relationship between the mean speed profiles (see Figure 3.5) and the MLP profiles. (The drop in the mean speed commenced at a distance further from the curve than did the start of the strong lateral shift).

The MLP profiles for the cases of total sample, 'with opposing vehicle' (WV) and 'without opposing vehicle' (WOV), are as shown in Figure 10b. The condition of WV against WOV has been determined by whether there were instances of meeting vehicle(s) on the other (opposing) lane within the length of the curve. The application of this differentiation is therefore restricted to within the length of the curve. The profiles indicate that the presence of an opposing vehicle(s) within the length of the curve resulted in larger lateral placement from the centre-line. The difference in the MLP at the curve mid-point between WV and WOV is of the order of 25-30 cm. The mean lateral separation between the reference wheels on the inside and the outside of the curve is represented by the vertical interval between the inside and the outside profiles for the case of 'with opposing vehicle' (WV). The mean lateral separation for the BS curve varies between 2.8-3.5 m, with maximum mean lateral separation in the vicinity of the curve mid-point.

3.4.3.2 Mean Lateral Placement on After-Study Curve

The MLP profiles for the AS curve (Figure 11a) indicate that different steering strategies were used between the inside and outside curves. Both profiles show corner-cutting over the length of the curve, with strong lateral shift commencing at the point of curve entry. The inside profile reflects a mean path radius generally greater than the centre-line radius (being typical of the steering behaviour for BS curves) while the outside profile is suggestive of a steering-in-chord type of steering behaviour. There are regions in the outside profile that have a mean path radius less than the centre-line radius, which is very undesirable from a safety point of view since the lateral acceleration is inversely proportional to the vehicle path radius. The variances in the MLP are fairly constant along the length of the road section being studied.

The MLP profiles for the cases of total sample, WV and WOV are as shown in Figure 11b. The presence of opposing vehicle(s) resulted in larger lateral placement from the centre-line, especially along the outside curve, with a lesser effect along the approach half of the inside curve. The mean lateral separation for the case of WV as indicated by the vertical interval between the inside and the outside MLP (WV) profiles varies between 2.7-3.5 m, with the maximum separation occurring at the curve mid-point region.

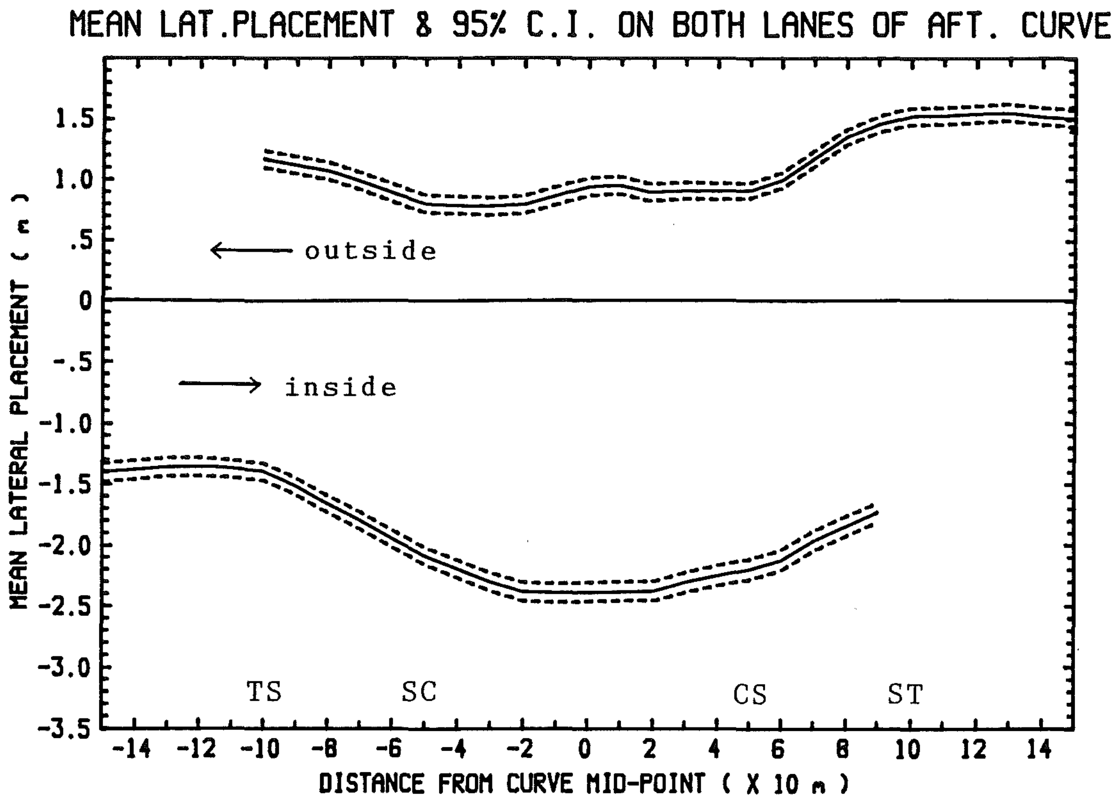

FIGURE 3.11a

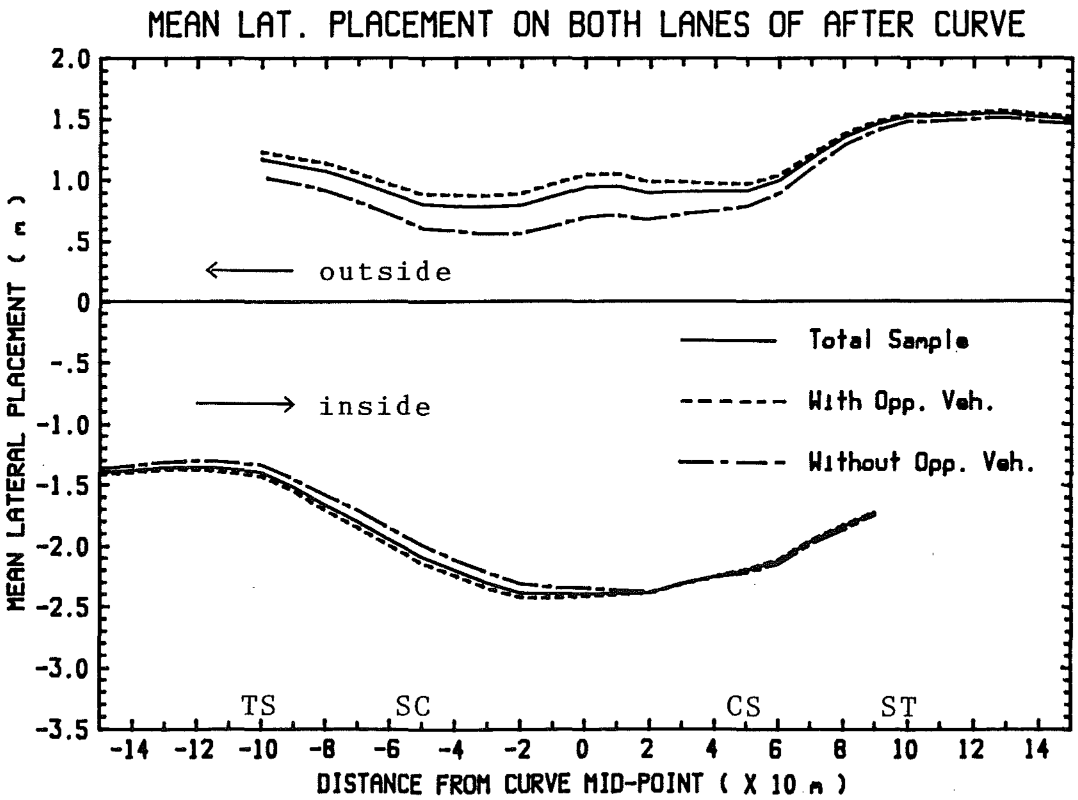

FIGURE 3.11b

3.4.3.3 Mean Lateral Placement on Before and After-Study Curves

A combined plot (Figure 3.12) showing the MLP profiles (total sample) for both the BS and AS curves shows that corner-cutting is much more prominent in the BS curve. In general, the lateral shifting of the cornering strategy is limited to within the bounds of the curves. The AS curve has more homogenous roadway width (See Figure 3.4) and this in effect provides a wider pavement for the motorists on the AS curve. The wider effective pavement width is accompanied by a reduction in the degree of corner-cutting which is a desirable operational characteristic (e.g. less shoulder maintenance).

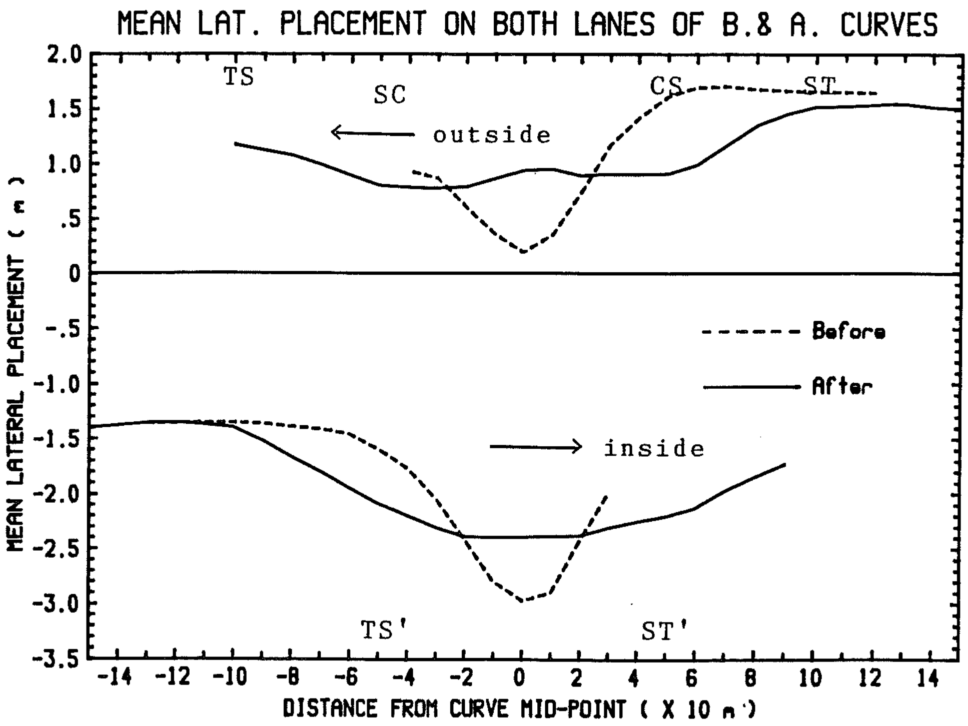

FIGURE 3.12

3.4.4 Centrality Index

The equation describing the centrality of the subject vehicles (Sections 2.4.3.1) is restated here as follows:

$$CI = (2 \times X1 + VW - TW) / TW \quad ....(3.1)$$

where CI, X1, VW and TW are the centrality index, lateral placement, vehicle wheel span and width between selected left and right boundaries, respectively. By using the centrality index to indicate the lateral positioning of the vehicle, the reference point of the vehicle is its longitudinal axis at ground level (as compared to the reference wheel being used as the vehicle reference point in conjunction with vehicle lateral placement - see section 2.4.1).

The mean CI profiles with the 95% confidence intervals for the case of TW = lane width and TW = (width of lane plus sealed shoulder) are presented in Figures 3.13a - 3.13d. The CI profiles show that:

(a) vehicles were more centrally placed in the AS curves; this effect was more prominent for the outside curve;

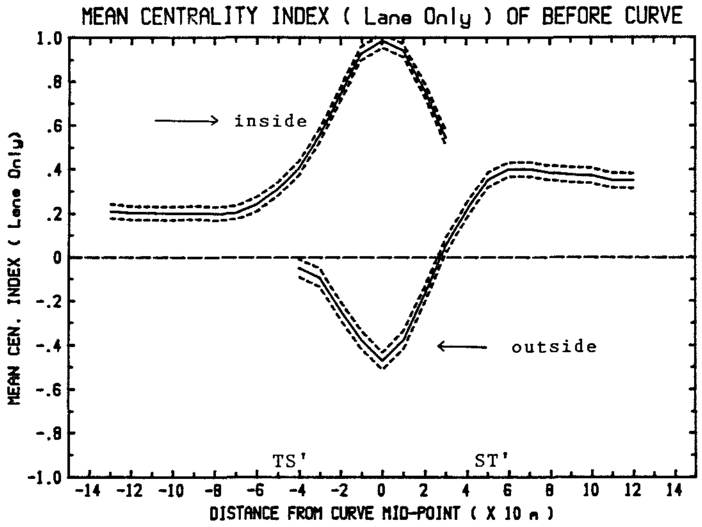

FIGURE 3.13a

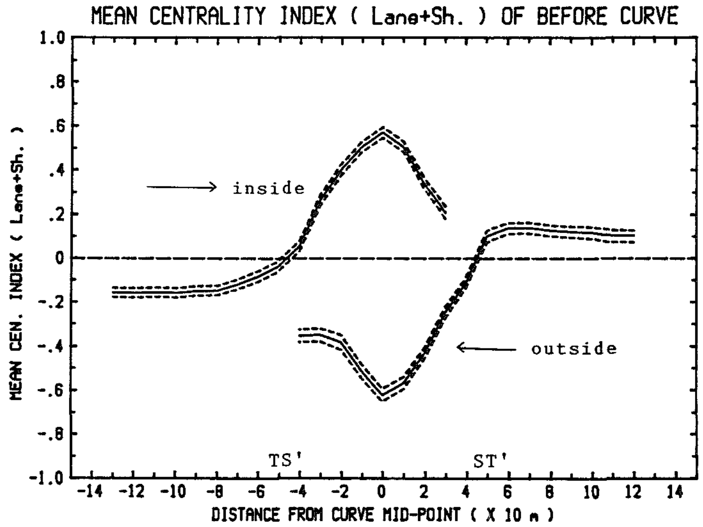

FIGURE 3.13b

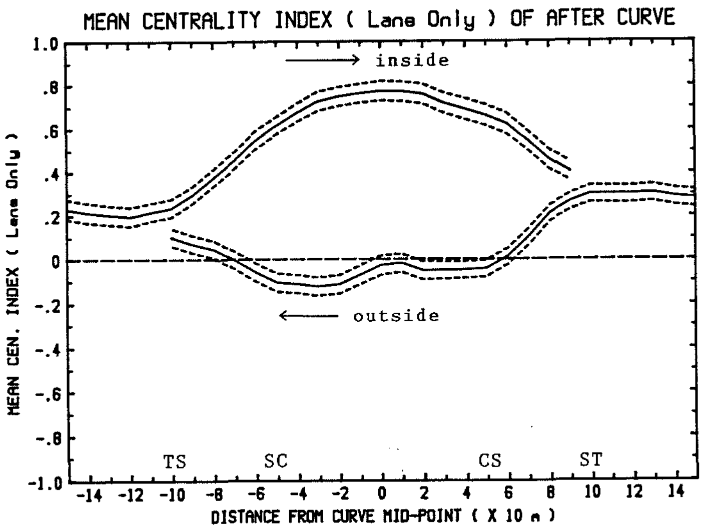

FIGURE 3.13c

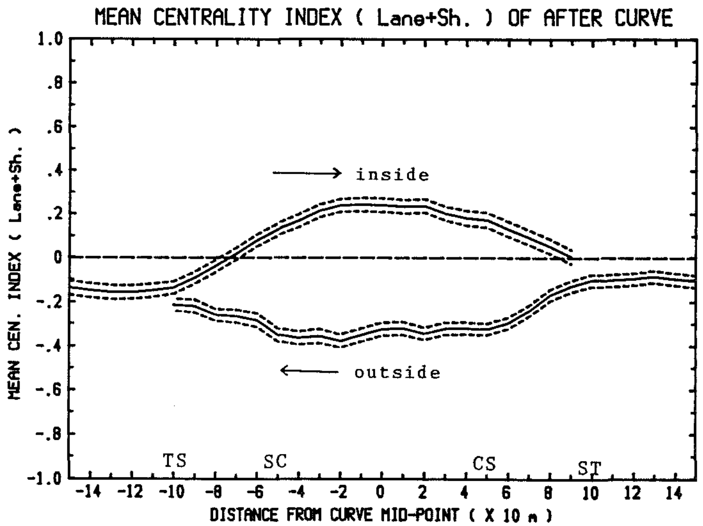

FIGURE 3.13d

(b) vehicles on the inside lane (especially for the AS curve) were moving closer to the centre-line before commencing corner-cutting, and vehicles on the outside lane (especially for the BS curve) were moving closer to the edge of the road before commencing corner-cutting;

(c) vehicles on the approach to the curves were, in general, closer to the edge-line than the centre-line but further away from the edge-of-seal than the centre-line. (The exception was the approach to the outside BS curve, where vehicles maintained a mean centrality position closer to the edge-line and edge-of-seal than the centre-line, and this could be due to the narrower shoulder width).

3.4.5 Centre-Line Encroachment Profiles

Centre-line encroachment profiles, showing the proportion of each sample, encroaching on the centre-line, are presented in Figures 3.14 and 3.15. No centre-line encroachment was observed for the inside of either the BS or the AS curves.

CENTRE-LINE ENCROACHMENT (OUTER LANE TRAFFIC) ON BEFORE CURVE

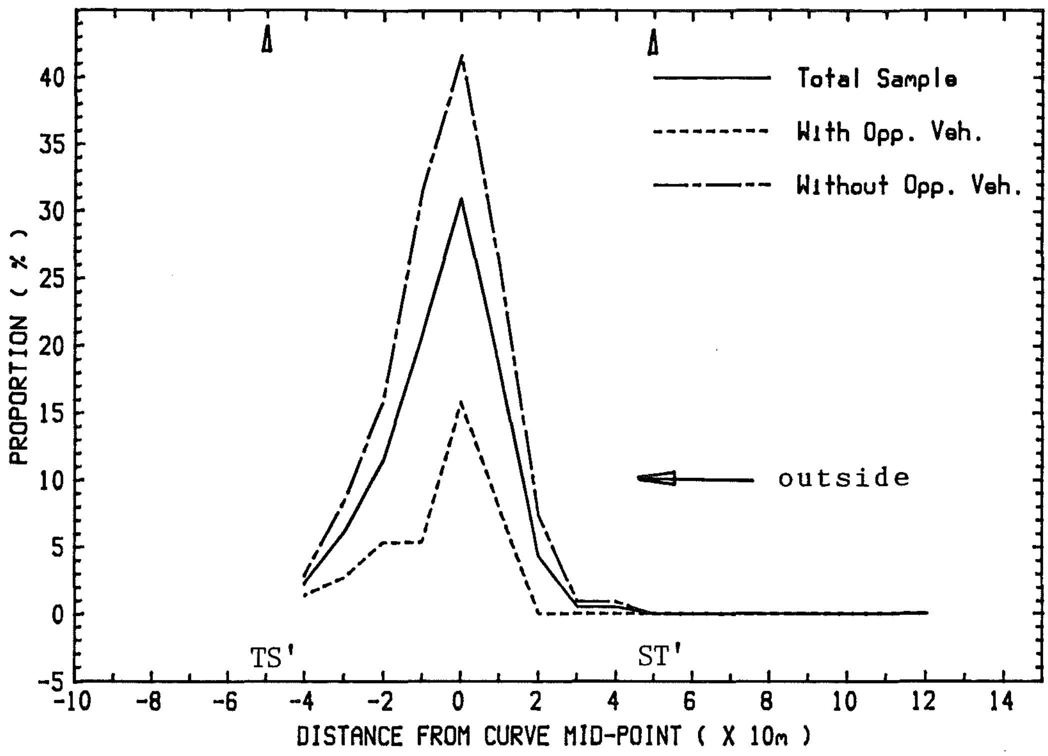

FIGURE 3.14

CENTRE-LINE ENCROACHMENT (OUTER LANE TRAFFIC) ON AFTER CURVE

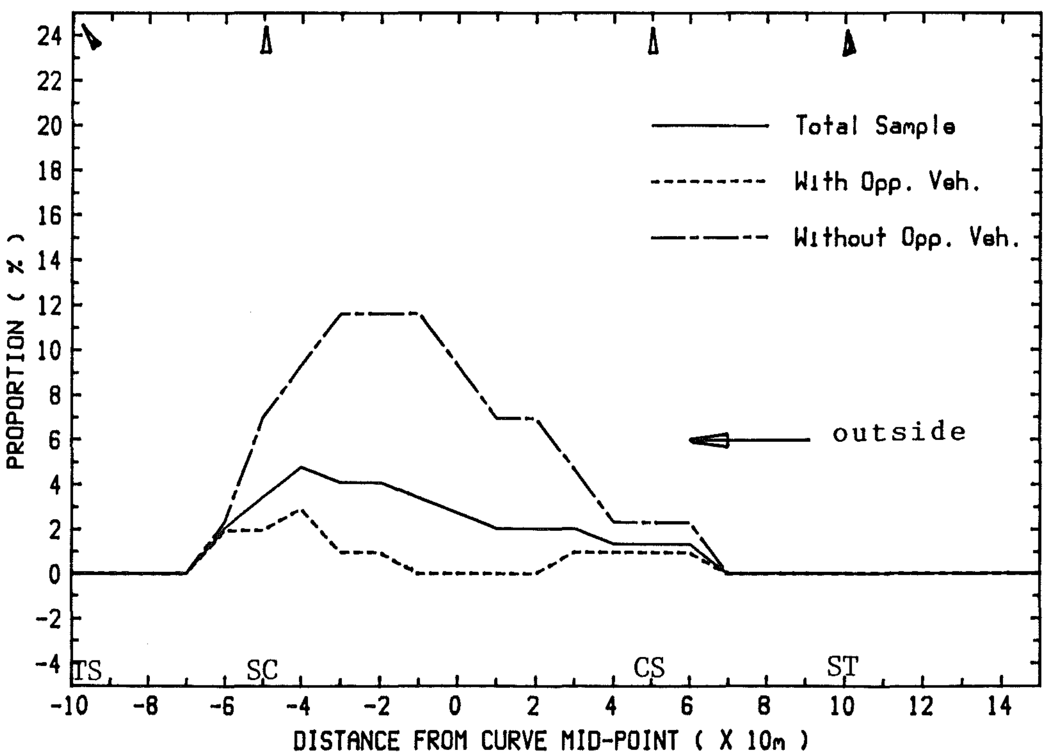

FIGURE 3.15

The profiles for the outside curve show that the centre-line encroachment occurred only within the curve length. In the 'before' profile (Figure 3.14), there was a sharp rise and fall within the middle half of the curve, with maximum proportions at the curve mid-point. The 'after' profile shows that centre-line encroachment occurred from half way into the approach spiral to half way through the departure spiral (i.e. over 75 percent of the curve length). Maximum proportions were reached in the departure half of the circular arc. In general, the level of encroachment was very much less for the AS curve.

The maximum proportions and the proportions at the curve mid-point were as shown in Table 3.5.

Cases	Sample	Maximum (%)	At Curve Mid-Point(%)
Outside BS	Total	31	31
	WV	16	16
	WOV	42	42
Outside AS	Total	4.8	2.9
	WV	3.0	0.0
	WOV	11.8	9.5

Table 3.5 Proportions Encroaching on the Centre-Line

The above Table shows that

(a) there was substantially less of a tendency to encroach upon the centre-line in the AS curve.

(b) the presence and absence of opposing vehicular flow had a great influence on centre-line encroachment.

3.4.6 Shoulder Encroachment Profiles

The shoulder encroachment profiles for all four cases are presented in Figures. 3.16-3.19.

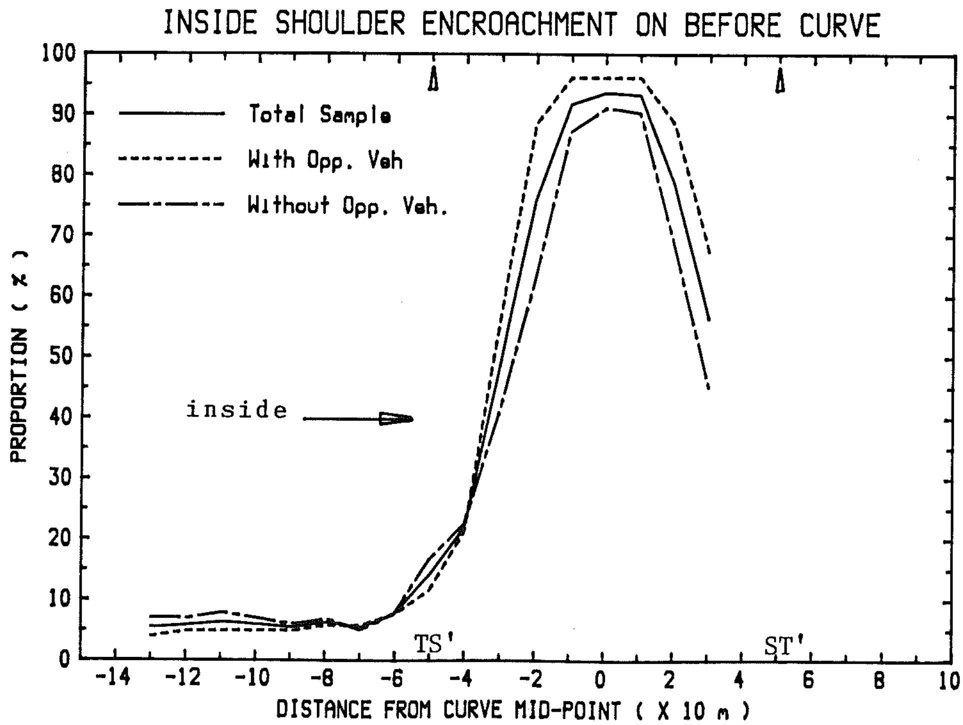

FIGURE 3.16

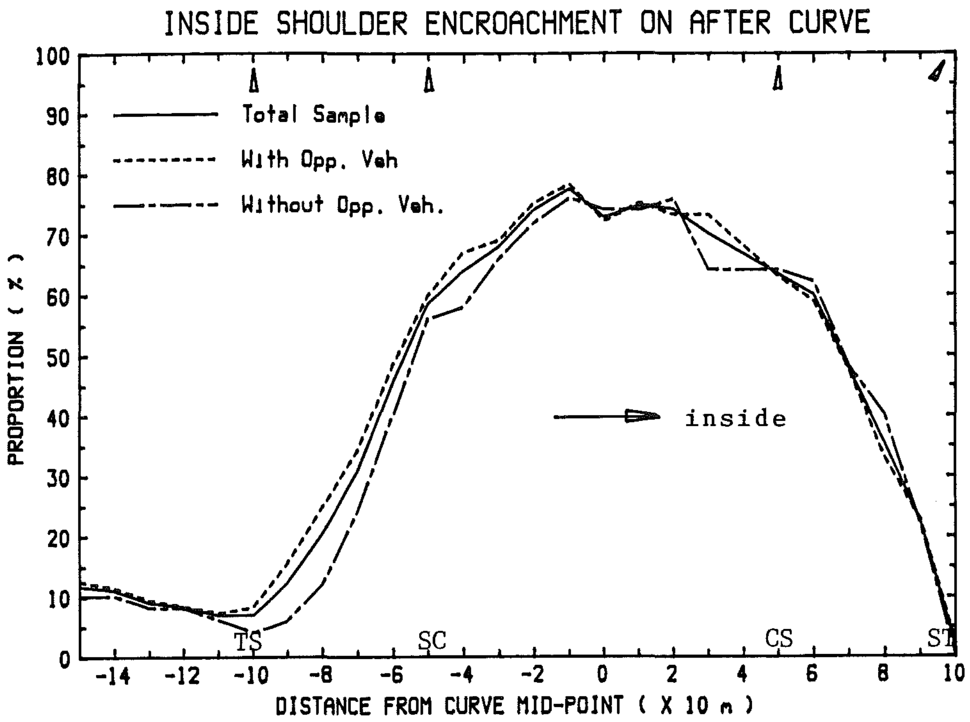

FIGURE 3.17

3.4.6.1 Inside Shoulder Encroachment Profiles

The profiles in Figures 3.16 and 3.17 show the inside shoulder encroachment pattern. The profiles exhibited very similar trends to their counterpart MLP profiles (Figure 3.10a). The 'before' profile shows a uniform, low level of encroachment along the approach tangent, followed by a steep rise and fall within the curve. The 'after' profile shows a drop along the approach tangent followed by a fairly steep rise and fall over the length of AS curve. In both profiles peak values were centred around the curve mid-point.

The proportions (percentages) at various specified points along the curves were as shown in Table 3.6.

Case	Sample	50 m from Curve	Curve Entry	Curve Mid-Point
Inside BS	Total	6	15	94
	WV	5	12	97
	WOV	7	18	92
Inside AS	Total	12	7	73
	WV	13	8	72.5
	WOV	10	5	74

Table 3.6 **Proportions Encroaching on Inside Shoulder**

The above figures showed that

(a) There was less tendency to encroach upon the shoulder at curve mid-point and curve entry for the AS curve. However, the AS curve had higher proportions of shoulder encroachment 50m upstream from curve entry.

(b) The influence of opposing vehicular flow was generally not very prominent.

3.4.6.2 Outside Shoulder Encroachment Profiles

Outside shoulder encroachment profiles are represented by Figures 3.18 and 3.19. It should be noted that the ordinate scales of the two profiles are not the same.

Referring to Figure 3.18, the 'before' profile exhibited an initial increase in encroachment reaching a peak at 10 m prior to the curve entry, followed by a steep drop; no encroachment was observed within the central half of the curve. The 'after' profile showed the same general trend, but with smaller peak values.

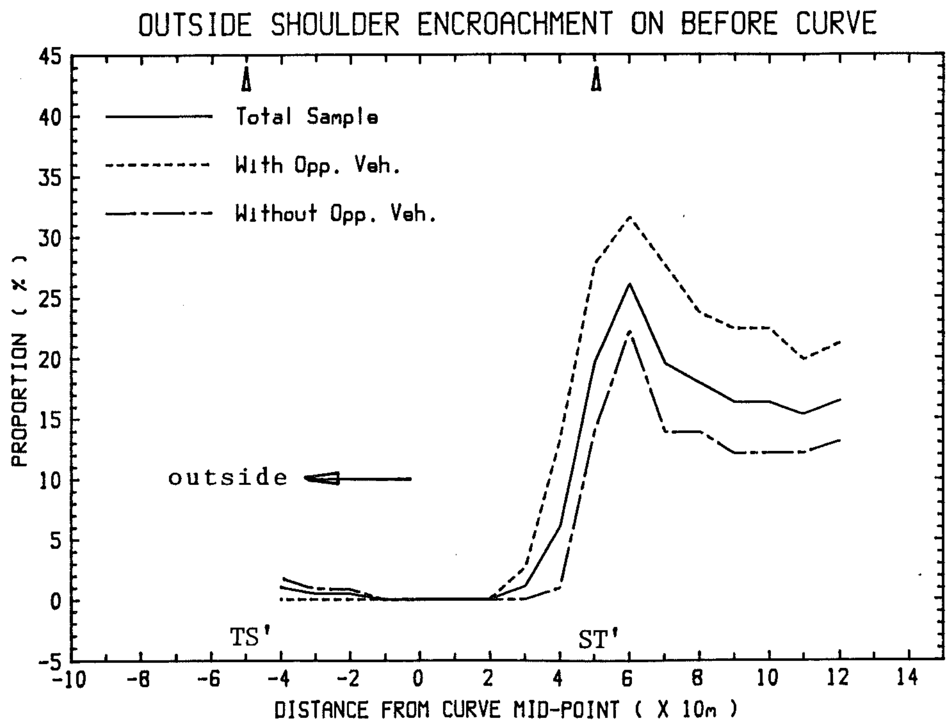

FIGURE 3.18

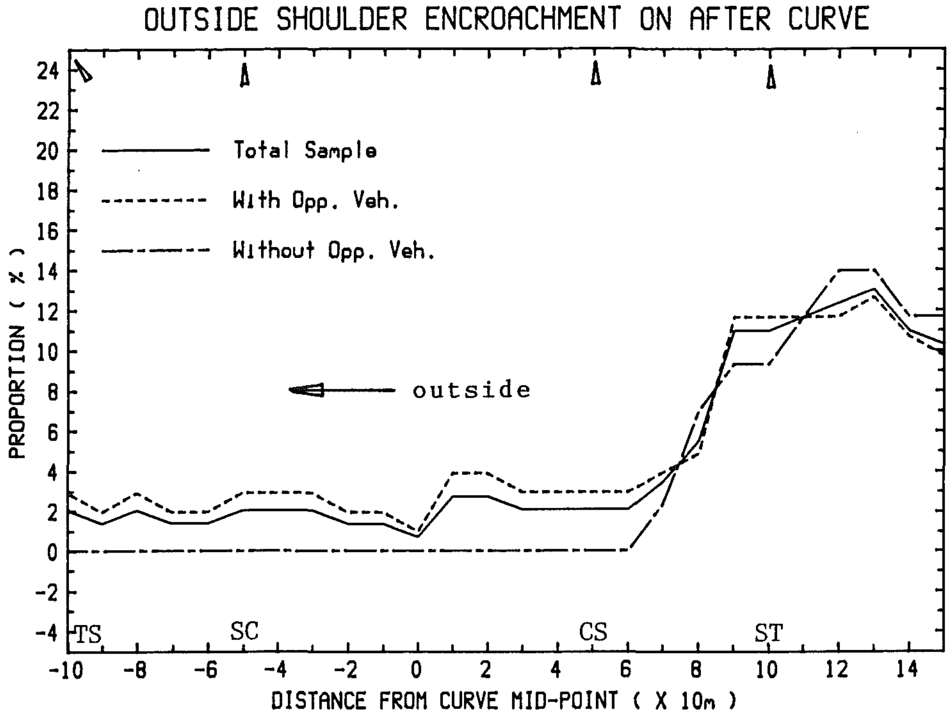

FIGURE 3.19

The proportions of outside shoulder encroachment at various specified points were as shown in Table 3.7.

Case	Sample	Maximum	Curve Entry	Curve Mid-point
Outside BS	Total	26	20	0
	WV	32	28	0
	WOV	22	13	0
Outside AS	Total	13	11	1
	WV	12.5	12	1
	WOV	14	9	0

Table 3.7 Proportions Encroaching on Outside Shoulder SEE ERRATA

The above results show that

(a) the proportion of maximum shoulder encroachment at the "maximum encroachment point" was about fifty percent less, in the AS curve,

(b) opposing vehicular flow had a substantial and consistent influence on the BS curve shoulder encroachment, but for the AS curve the effect was not as substantial or consistent.

3.5 BEHAVIOUR AT THE CURVE MID-POINT

3.5.1 Lateral Placement

Cdf plots are presented in Figure 3.20 showing the lateral placement of the right-front wheel from the centre-line. The lateral placement on the inside curves are plotted on a negative scale.

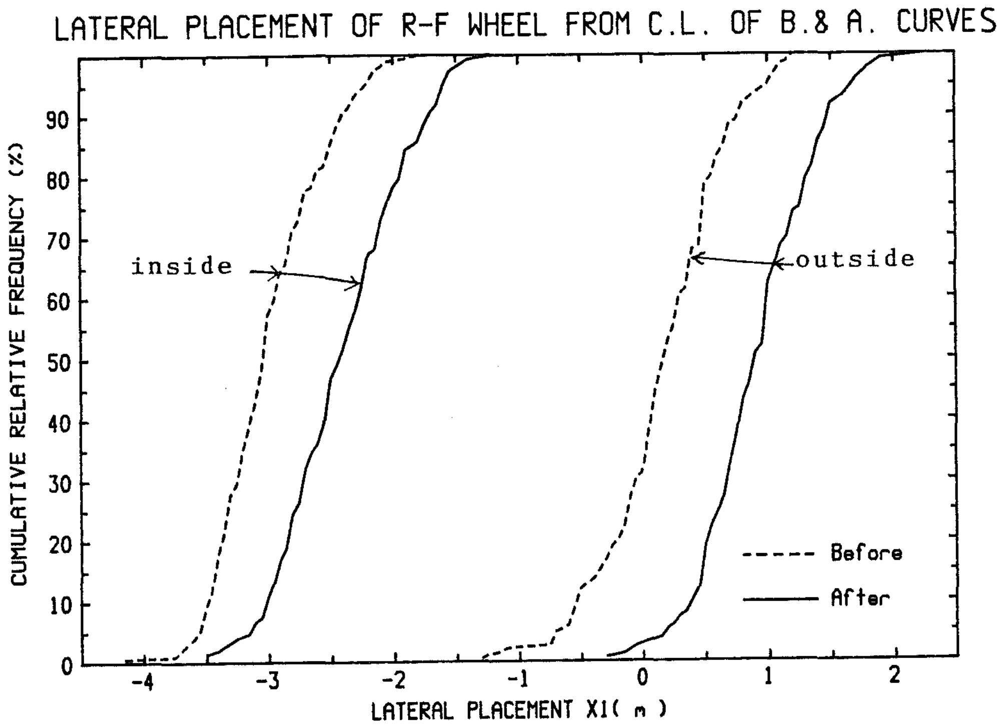

FIGURE 3.20

The plots show that, as a result of re-alignment,

(a) there was a shift in lateral placement towards the centre-line for the inside curve and away from the centre-line for the outside curve;

(b) the width between the cdf plots for the inside curve and the outside curve remained about the same. This suggests that the vehicle-to-vehicle clearance had not changed substantially. The lateral clearances at the curve mid-point for the case of WV (i.e. with opposing vehicle(s)) were 3.43 m and 3.44 m for the BS and AS curves respectively.

The mean and standard deviation of lateral placement were as shown in Table 3.8.

Case	**Mean**	**Standard Deviation**
Inside BS	2.97	0.42
Inside AS	2.38	0.49
Outside BS	0.19	0.49
Outside AS	0.93	0.45

Table 3.8 **Lateral Placement : Mean and Standard Deviation**

3.5.2 Centrality Index

The mean centrality indices at the curve mid-point were as shown in Table 3.9.

The mean values indicate a regression towards the null value in the AS curve. This is equivalent to vehicles being more centrally placed in the AS curve than the BS curve. The t-statistics for the comparison of mean centrality indices between the BS and AS curves had significance probability less than 0.001.

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Case	Lane Only		Lane & Sealed Shoulder	
	Mean	Std. Dev.	Mean	Std. Dev
Inside BS	.571	.174	.987	.219
Inside AS	.239	.194	.774	.277
Outside BS	-.622	.199	-.472	.277
Outside AS	-.324	.181	-.028	.261

Table 3.9 Centrality Indices : Mean and Standard Deviation

3.5.3 Speed

The speed cdf plots (Figures 3.21 and 3.22) show that there was a large increase in speed for the outside curve but a minor change for the inside curve.

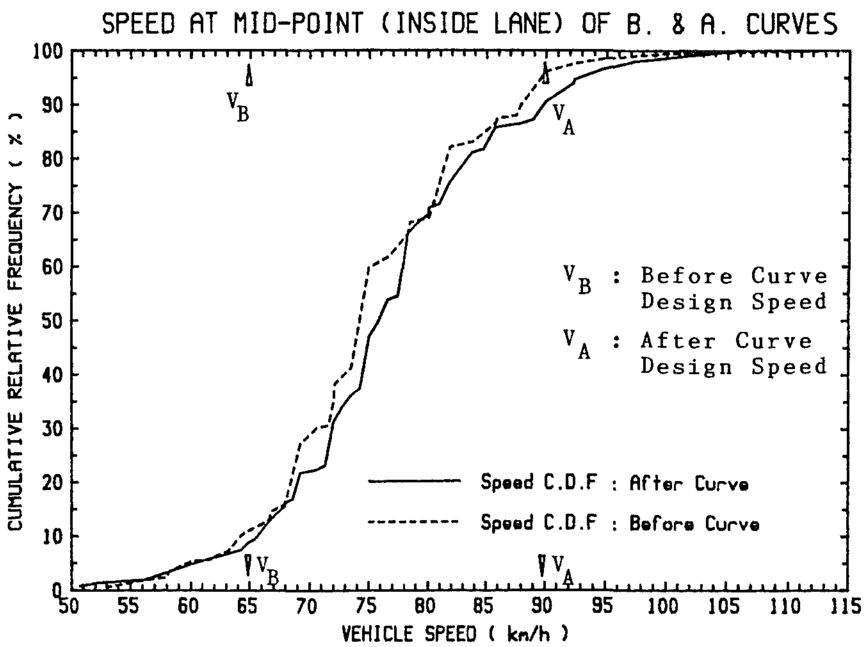


FIGURE 3.21

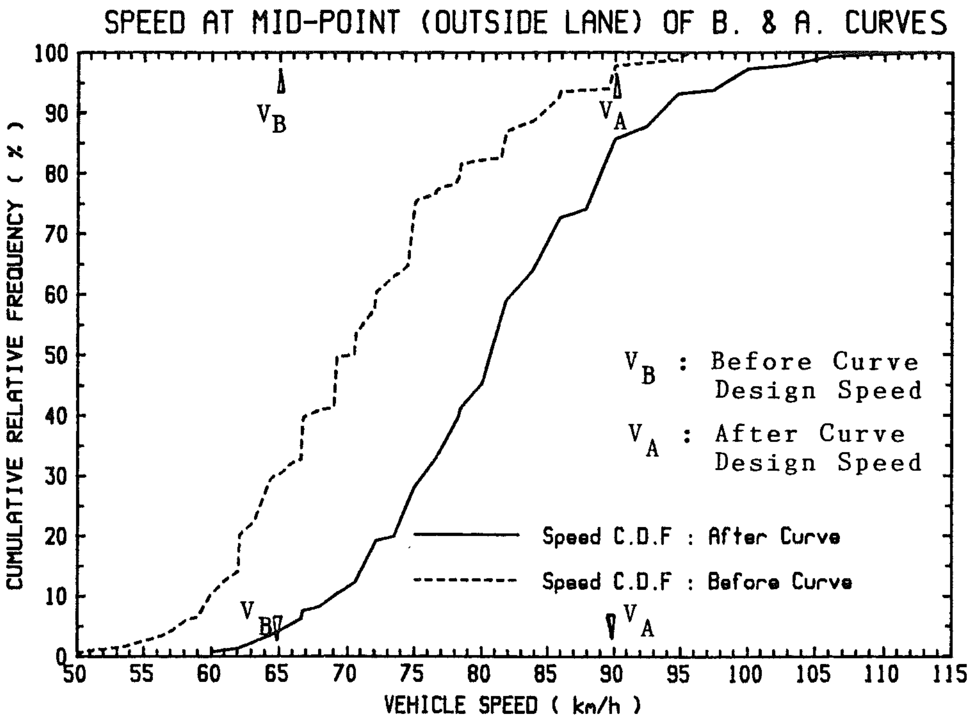


FIGURE 3.22

The mean speeds and standard deviations were as given in Table 3.10.

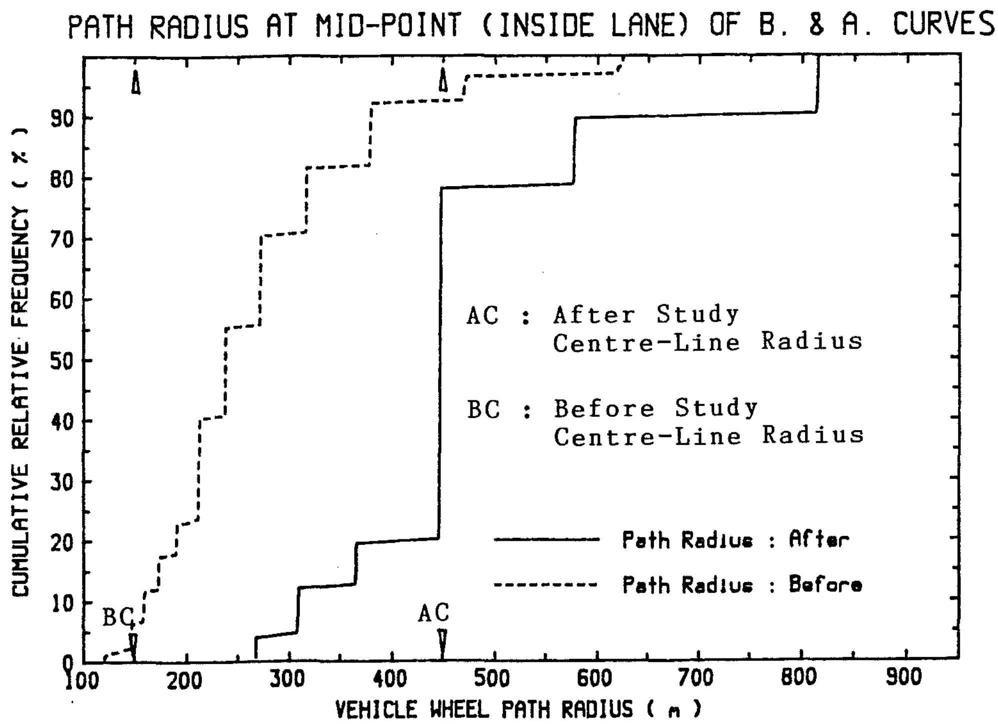
Case	Mean	Standard Deviation
Inside BS	75.83	9.09
Inside AS	77.04	9.63
Outside BS	71.25	9.37
Outside AS	81.87	9.75

Table 3.10 Speed : Mean and Standard Deviation

The t-statistics for a before and after comparison of the mean speeds had significance probability of 0.23 for the inside curve and 0.0001 for the outside curve.

3.5.4 <u>Wheel Path Radius</u>

With reference to Figure 3.23, a definite shift in path radius was observed for the inside curve. The 'stepped' distribution is a result of the discrete nature of the lateral placement data (to the nearest 5 cm in most of the cases). There was a more uniform distribution of path radii for the BS curve, while 60% of vehicles on the AS curve had a path radius between 400-500 m.



<u>FIGURE 3.23</u>

Path radii for the outside curve are shown in Figure 3.24, with the 'after' plot exhibiting a smaller range of values than the 'before' plot. For both the BS and AS curves, the distribution of path radii was fairly uniform.

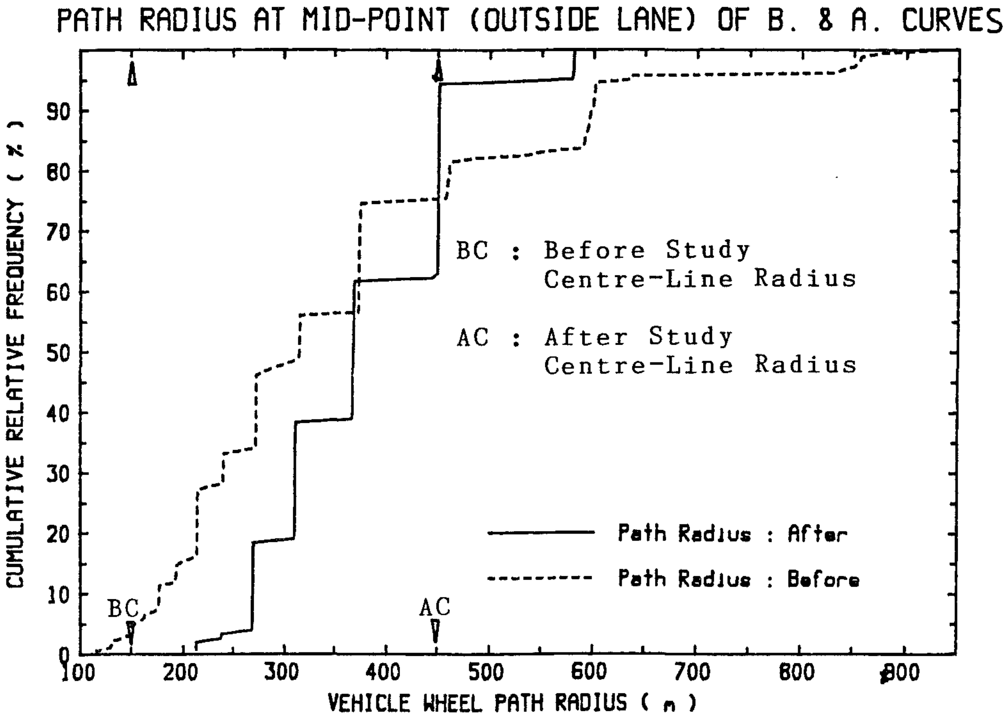


FIGURE 3.24

The mean path radii and the standard deviations, and the proportions greater than the centre-line radius, were as shown in Table 3.11.

Case	Mean	Standard Deviation	Proportion (%) > Centre-Line Radius
Inside BS	269	104	94
Inside AS	475	136	21
Outside BS	354	173	95
Outside AS	376	87	5

Table 3.11 Path Radii : Mean and Standard Deviation

The t-statistics (for unequal variances) for mean path radii gave significance probability of 0.0001 for the inside curve and 0.13 for the outside curve.

The above results show that, at the curve mid-point, the re-alignment resulted in

(a) a significant increase in the mean path radii ($p < 0.0001$, t-test) and variance ($p < 0.0001$, F test) for the inside curve;

(b) no significant change in the mean path radii ($p = 0.13$, t-test) but a significant decrease in the variance ($p < 0.0001$, F test) for the outside curve.

(c) a high proportion of the path radii for the AS curves were less than the centre-line radius.

3.5.5 Relationship Between Speed and Path Radius

The relationship between the speed and vehicle wheel path radius is shown as scatter plots in Figures 3.25a - 3.25d. The plots show data points spread out in a rectangular 'grid'. This reflects the discrete nature of the frame count (to the nearest half frame for computation of speed) and lateral placement (to the nearest 5 cm for computation of path radius). It is also noted that the intervals between adjacent data

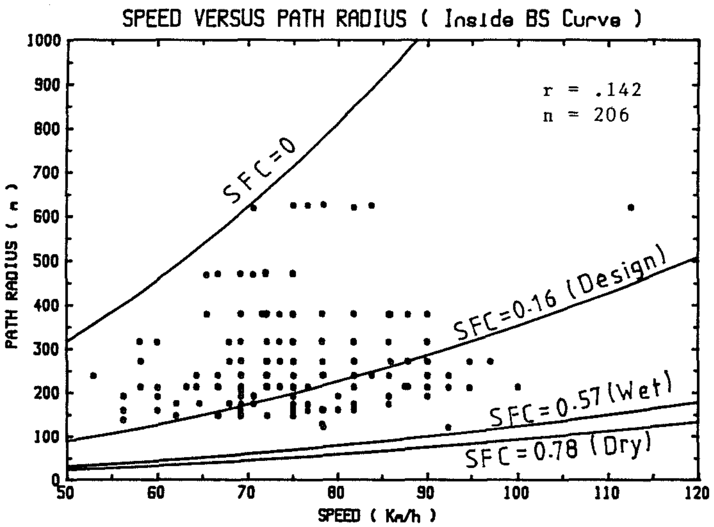


FIGURE 3.25a

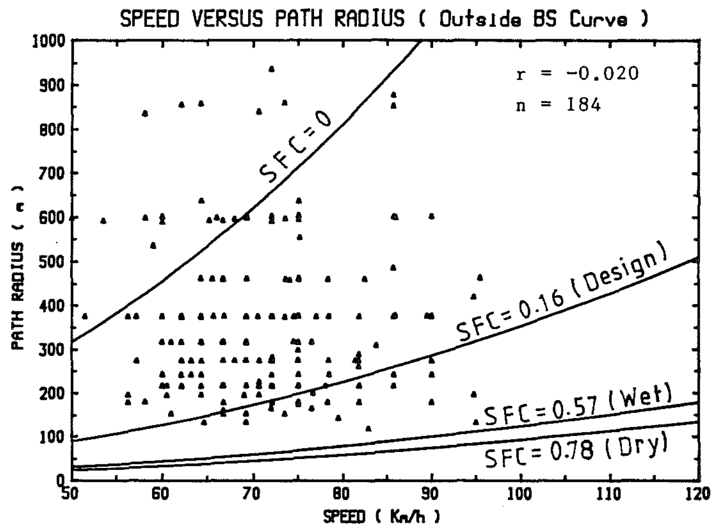


FIGURE 3.25b

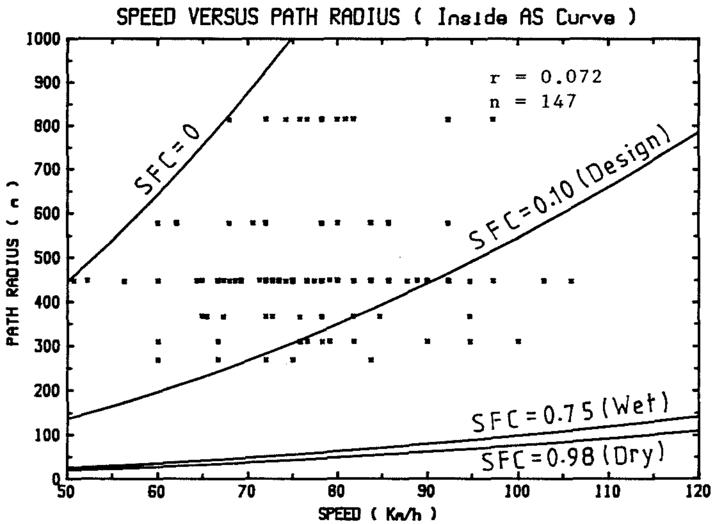


FIGURE 3.25c

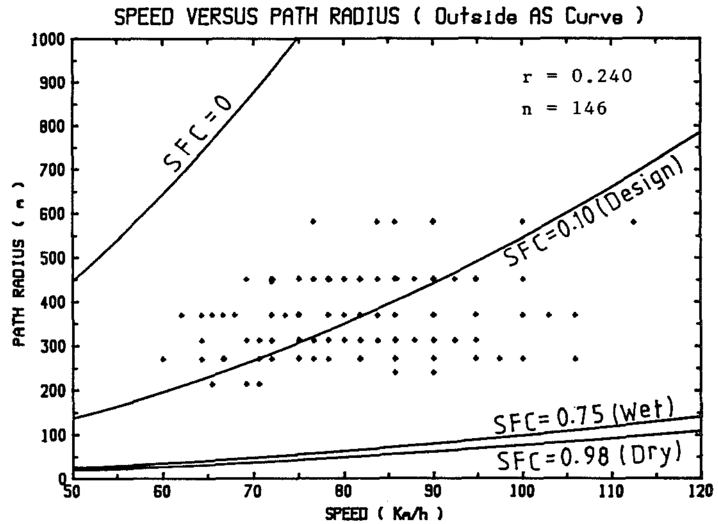


FIGURE 3.25d

points tend to increase in the direction of higher speed and larger path radius. Again this is due to the discrete nature of the basic data. There is also overlapping in quite a few data points.

The correlation between the speed and path radius is very low : (a correlation coefficient of 0.14 and 0.07 for the inside lane of the BS and AS curves, respectively and -0.02 and 0.24 for the outside lane of the BS and AS curves, respectively). There is therefore no evidence to suggest that vehicle path radius is linearly correlated to the vehicle speed. This result is quite surprising since it is frequently assumed that a larger path radius (i.e. greater corner cutting) is associated with a higher vehicle speed in order to avoid excessive side friction demand.

The scatter plots also show curves corresponding to various values of sideway force coefficients (SFC). The values of SFC are

(a) zero i.e. no side friction demand;

(b) design SFC (see Table 3.1);

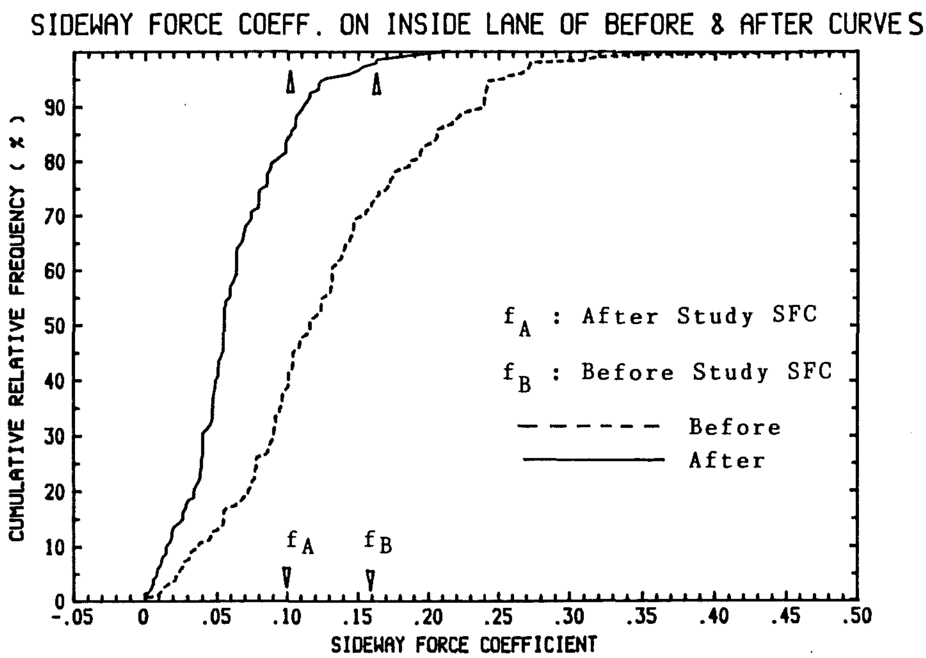
(c) skid resistance for wet and dry surfaces (as measured using a British Pendulum tester and using the conversion BPN = 100 x skid resistance).

The plots show that quite a few subject vehicles required side friction greater than the design SFC but no subject vehicles exceeded the available skid resistance as determined by the B.P. tester. It is interesting to note that quite a few subject vehicles experienced negative side friction on the outside lane of the BS curve.

3.5.6 <u>Required Sideway Force Coefficient SFC</u>

The required SFC's at the curve mid-point were as presented in Figures 3.25 and 3.26.

The SFC plots for the inside curve show a general reduction for the AS curve. For the outside curve, there was an increase at lower SFC's and a decrease at higher SFC's.



<u>FIGURE 3.26</u>

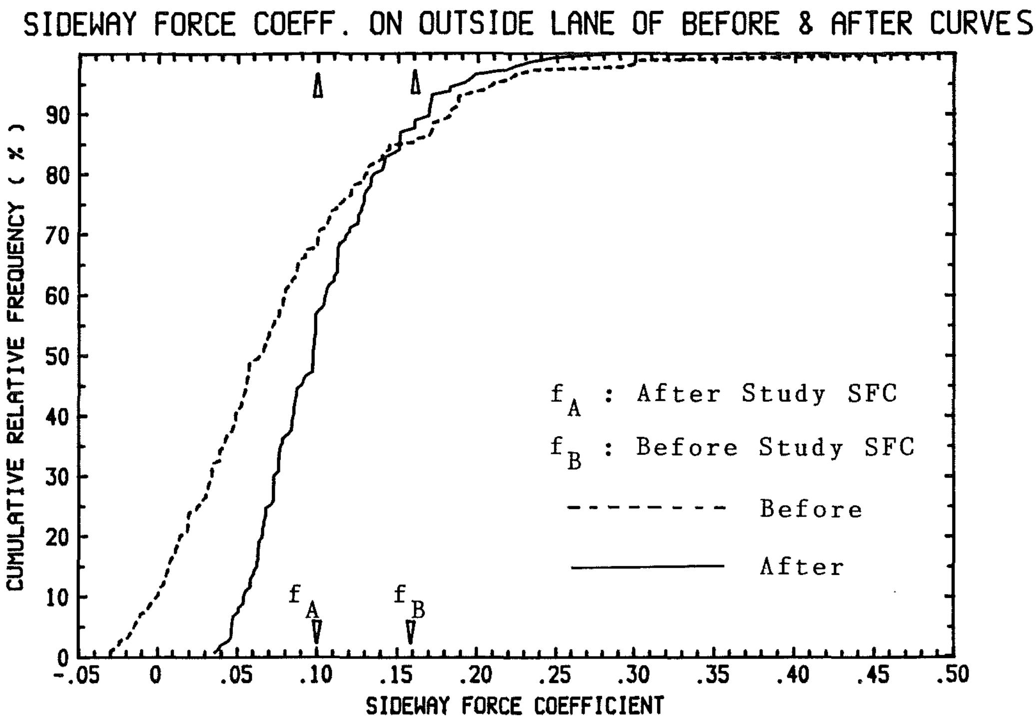


FIGURE 3.27

From the plots, the proportion (%) of required SFC's greater than the design SFC (0.16 for BS curve, 0.10 for AS curve) was estimated, and is shown in Table 3.12 with the mean SFC's and standard deviations.

Case	Mean	Standard Deviation	Proportion (%) > Design SFC
Inside BS	0.128	0.073	26
Inside AS	0.063	0.038	12
Outside BS	0.080	0.078	15
Outside AS	0.104	0.046	50

Table 3.12 **Sideway Force Coefficient**

Comparison of the mean required SFC's for the before and the after curves using the unequal-variance t-test, gave a significance probability of 0.0001 for the inside curve and 0.0004 for the outside curve.

3.6 OPERATING SPEED ENVIRONMENT

The concept of speed environment has been pointed out in conjunction with the discussion on design speed in horizontal curve design. The speed environment is used to characterize the desired speed behaviour over a section of road and 'is regarded as being uniform over a section of road that is reasonably consistent in both terrain and general geometric standard. It is numerically equal to the desired speed of the 85th percentile driver over that road section and thus, by definition, equal to the 85th percentile of the observed speed distribution on the longer straights (or large radius curves) on the section' (NAASRA, 1980). It follows from the above definition that the speed environment of the section of road containing the Foremans Road curve can be estimated by observing the speed distributions along the long tangents between Hornby and Templeton (see Figure 3.1).

The results of the speed surveys (Section 2.1.6) along the long tangents adjoining the Foremans Road curve (See Figure 3.2) are shown in Table 3.13. The speed values (obtained from video records) at the mid-point of the Foremans Road curve are also included in the table. The figures denote the 85th percentile and mean speeds, and the arrows indicate the direction of traffic flow.

Case	Hornby End Survey Site		Foremans Road Curve		Templeton End Survey Site
BS inside	88.7/78.7	→	85.2/75.8	→	85.7/76.9
AS inside	87.9/78.4	→	85.5/77.0	→	90.6/80.7
BS outside	85.8/77.3	←	81.6/71.3	←	85.5/76.0
AS outside	94.0/82.5	←	89.7/81.9	←	90.9/80.3

Table 3.13 Speed at Curve Mid-Point and Adjoining Tangents

It is noted again that the realignment of the Foremans Road curve was carried out in conjunction with the shape correction of part of the adjoining tangent between the curve and Templeton. The speed survey site at the Templeton end was within the section of road that was shape-corrected. The shape-correction resulted in an increase of 0.5m in the sealed shoulder width (1.0 m to 1.5 m) while the lane width remained unchanged.

In comparing the speed values in the direction going from Hornby to Templeton between the before and after situations, it can be seen that the operating speed remained fairly constant in the pre-curve tangent section and within the curve, while the post-curve operating speed increased. In the direction going from Templeton to Hornby, there was an increase in the operating speed along both adjoining tangents as well as within the Foremans Road curve. Based on these figures, it seems that

(a) the shape correction works along the tangent on the Templeton end resulted in an increase in the operating speed along the tangent (5 km/h for the 85th percentile speed, and 4 km/h for the mean speed) in both directions;

(b) the shape correction works along the tangent was likely to be partly responsible for the large increase in the speed on the outside lane of the AS curve (8 km/h for the 85th percentile speed and over 10 km/h for the mean speed). However it is very difficult to separate the effects of the shape correction and the curve realignment on the large increase in the speed, given that the shape correction and the curve realignment were carried out in the same time period;

(c) the large increase in the operating speed of the post-curve tangent section on Hornby end (8km/h for the 85th percentile speed and 5 km/h for the mean speed) was a result of a higher operating speed in the preceding curve.

It is interesting to note that approval for the shape correction work had been given when the proposal for upgrading the curve was considered. Given the above findings, it can be seen that the option of upgrading the curve in conjunction with the shape correction was an appropriate one.

3.7 ACCIDENT OCCURRENCE AT STUDY SITE

The Ministry of Transport accident records show that in the period from 1980 to 1985 (i.e. in the 6 years prior to the curve realignment), there were three reported injury accidents close to the Foremans Road curve (no reported accidents inside the curve). None of the three reported accidents (two involved collisions with turning vehicles, and one involved a motor cycle riding too close to the edge of the road) were related to having difficulty with the curve. However, there were good grounds to believe that the before curve had a fair share of accidents, especially the single-vehicle lost-control accident type (probably minor injury or property damage only) based on the much dented shape of the guard rail on the outside berm of the curve. This accident experience was confirmed from interviews with the occupants of the adjacent properties; one of the properties was a car-wrecker's yard and it could be assumed that the owner could provide quite reliable information since he has a vested interest in accident occurrences.

There has been only one reported accident during the post-realignment period (3 1/2 years from 1986 to 1989). The single reported accident (rear end collision: following too closely) was not related to difficulty with the curve. A recent interview with the occupants of the adjacent properties indicated that the 'accident blackspot' has disappeared since realignment. It appears that the realignment of the curve (possibly in conjunction with the shape-correction of the adjacent tangent) has reduced the level of accident occurrence at the study site.

3.8 SUMMARY OF RESULTS

(a) Consideration of mean speed profiles showed that different speed control strategies were used for the inside and outside curves. There was no clear evidence of inadequate speed control.

(b) There was no region of uniform mean speed within the BS curve. The uniform mean speed region within the AS curve was about half the curve length and was centered at a point prior to the curve mid-point.

(c) The acceleration and deceleration patterns were not mirror images of each other; the higher acceleration and the location of minimum mean speed suggested desired travel speed greater than perceived safe speed in curve.

(d) The mean speed for the inside curve did not change significantly, but the mean speed for the outside curve increased significantly.

(e) There was a large reduction in the proportion of vehicles exceeding the design speed.

(f) The mean lateral placement profiles showed strong lateral shifts near to the centre of the curve, and this phenomenon was more pronounced for the BS curve; lateral shifting is also mainly limited to within the bounds of the curves.

(g) The mean lateral placement profiles were not related to the mean speed profiles, and did not seem to be influenced by the variations in the sealed shoulder width.

(h) Centrality index profiles show that vehicles were more centrally placed in the AS curves; this effect was more prominent on the outside curve.

(i) There was much less of a tendency to encroach upon the centre-line by outside AS curve traffic.

(j) There was less of a tendency to encroach upon the sealed shoulder on the AS curve.

(k) Lateral placement data at the curve mid-point suggest that vehicle-vehicle clearance did not change substantially.

(l) There was a significant increase in mean path radii and variance at the mid-point of the inside curve; a significant decrease of variance was observed for the outside curve, but the mean path radii remained fairly constant.

(m) A high proportion of path radii for the AS curve were below the centre-line radius at the curve mid-point.

(n) There was no evidence that speed was linearly related to vehicle path radius at the curve mid-point region.

(o) There was a significant reduction in the required SFC's for the inside curve and a significant increase in the required SFC's for the outside curve; this was reflected in the proportion of required SFC's greater than the design SFC's.

(p) The shape-correction of the adjoining tangent resulted in an increase in the operating speed and this seemed to have influenced the driver behaviour in the follow-on curve.

(q) The level of accident occurrence at the study site is likely to have reduced.

CHAPTER IV

4.1 STUDY SITE

This chapter describes a before-study on a pair of reverse curves prior to curve re-alignment (the BS curves) and an after-study on the reverse curves after curve re-alignment (the AS curves). The reverse curves are on State Highway SH1 at reference point RP 299/2.34-3.00 in Road District RD13 (Figure 4.1). The study site is also known as the "Leithfield Reverse Curves". The before-study and after-study were done in mid-1986 and at the end of 1986, respectively.

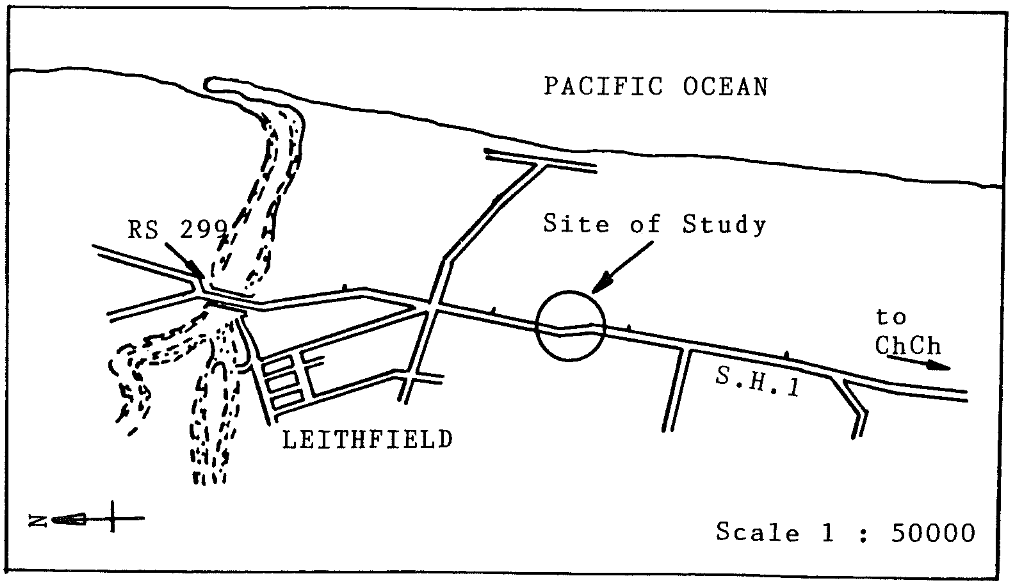


Fig. 4.1 Locality Plan of Study Site

The reverse curves are located in a flat, open terrain. Two thickly-bushed sand-hills lay on the inside of each of the BS curves. The reverse curves adjoin long sections of straight road at both ends (1.5 km at the north end and 6 km at the south end).

The study site is on a stretch of highway with open road speed limit of 100 km/h and an estimated operating speed environment of 110 km/h on the tangents adjoining the reverse curves. The BS reverse curves had 70 km/h advisory speed signs but there are no such signs on the re-aligned (AS) reverse curves. A traffic volume count station operated by the Ministry of Works and Development is located at a site 6 km south of the study site (station 6/1S/16 at RP 299/8.90). Count data suggest an average daily flow of between 3000 and 3500 vehicles.

For the purpose of this study, the curve at the north of the study site is henceforth referred to as the north or N curve while the curve at the south end is referred to as the south or S curve. The layout of the BS (N and S) and the AS (N and S) curves are shown in the superimposed plots of Figure 4.2. The tangent-spiral junctions and the curve mid-points of the BS curves are marked as ST′, TS′ and MP′ respectively, and subscripted by the letters N and S to denote that of the north and south curves. The tangent-spiral, spiral-circular and mid-points for the AS curves are similarly marked (minus the prime symbol) and accordingly subscripted.

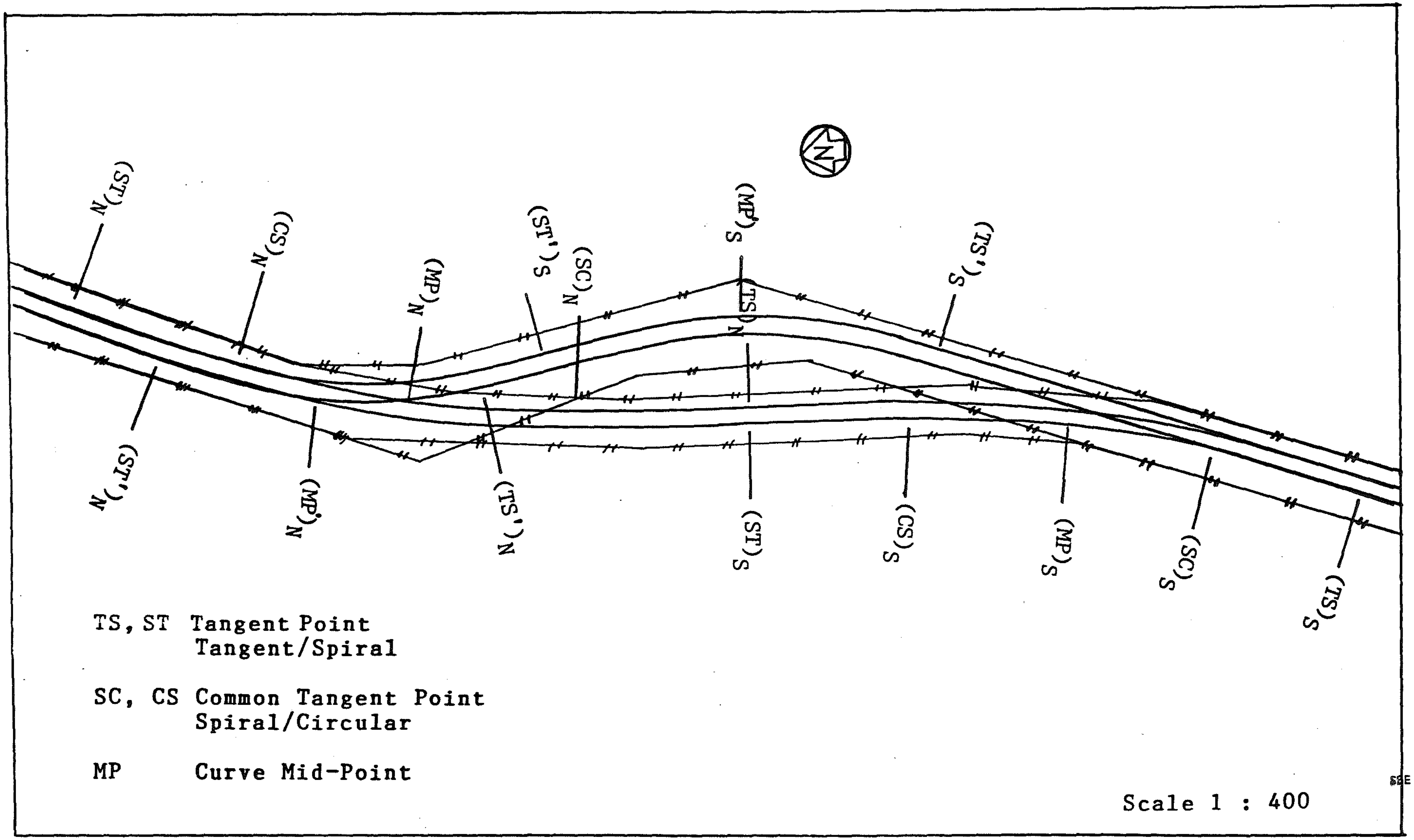


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Fig. 4.2 Before Study Curve (in Transparency) and After Study Curve

The curve data for the BS and AS reverse curves are as shown in Table 4.1.

	Before		After	
	North Curve	South Curve	North Curve	South Curve
Speed value (km/h)	70 (advisory)		100 (design)	
Centre-line radius (m)	180	185	560	580
Superelevation (%)	+8.70	+9.30	+6.40	+6.20
Side-way force Coefficient, SFC (at above speed value)	0.127	0.116	0.077	0.074
Curve length (m)	140	160	300	270
Skid resistance (BPN)	60 (wet)	56 (wet)	77 (wet)	
Texture depth (mm)	1.77	1.98	1.67	
Surfacing:				
Chip grade	3		4	
Binder	180/200		Soft residue asphaltic cutback	
Treatment	Reseal		New	
Date of Completion	1977		1986	
AADT	3590 (NRB - AADT 1983)			

Table 4.1 **Before-Study and After-Study Curve Data for Leithfield Reverse Curves, at Curve Mid-Point Region**

The lane and sealed roadway widths over the length of the road being studied were as shown in Figures 4.3 and 4.4, where the widths on the outside curves are plotted on a positive scale and those on the inside curves are plotted on a negative scale. The horizontal arrows on the plots indicate the direction of traffic flow relative to the abscissa while the notation 'NB' and 'SB' indicate north-bound and south-bound traffic flow respectively (See Figure 4.1). The lane and sealed roadway width profiles show that there was only a slight increase in the lane width while there has been a substantial increase in the sealed roadway width (i.e. a large increase in the sealed shoulder width).

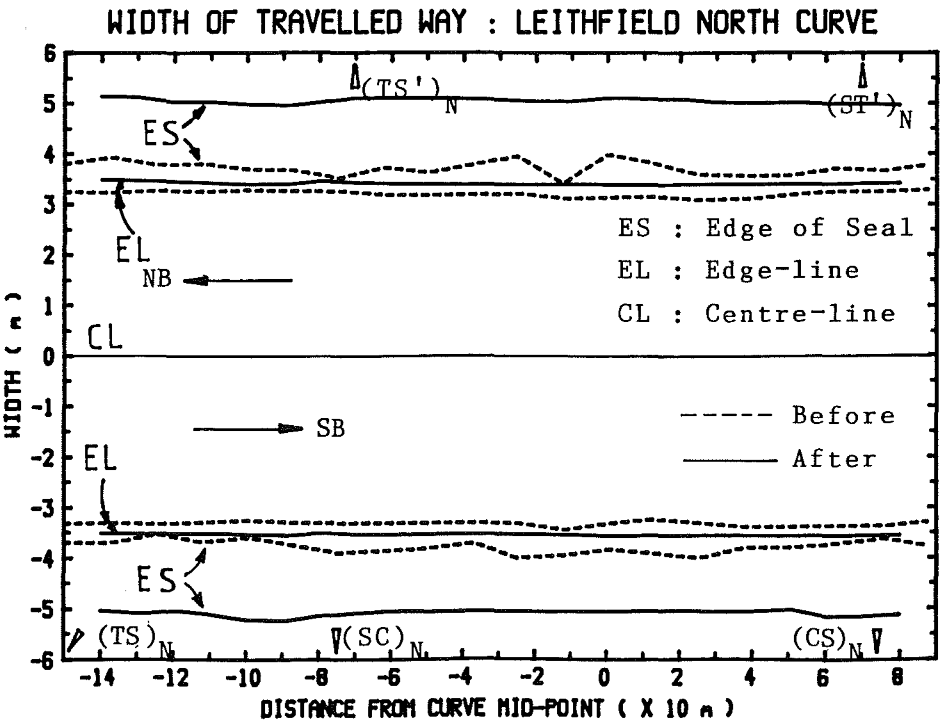

FIGURE 4.3

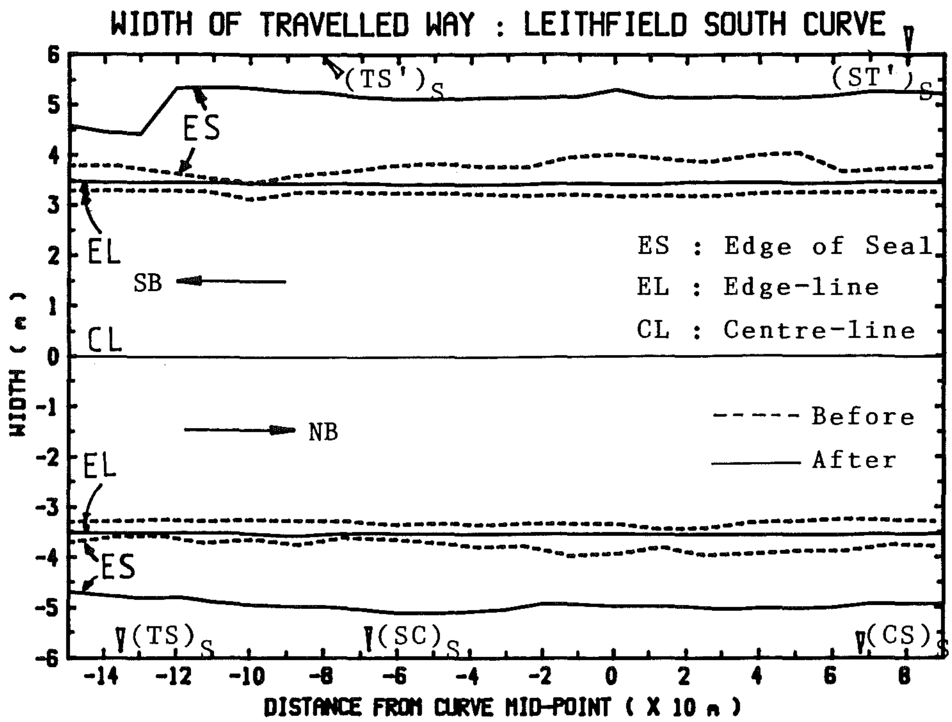

FIGURE 4.4

The stopping sight distance (SSD) for the BS reverse curves varied as shown in Figures 4.5 and 4.6, where the SSD's on the inside curves are plotted on a negative scale. The profile for NB on the N curve is mirror image of that for NB on the S curve (and ditto for SB on the N curve and SB on the S curve). There is no SSD restriction on the AS curves.

Data were collected for each of the reverse curves on separate days.

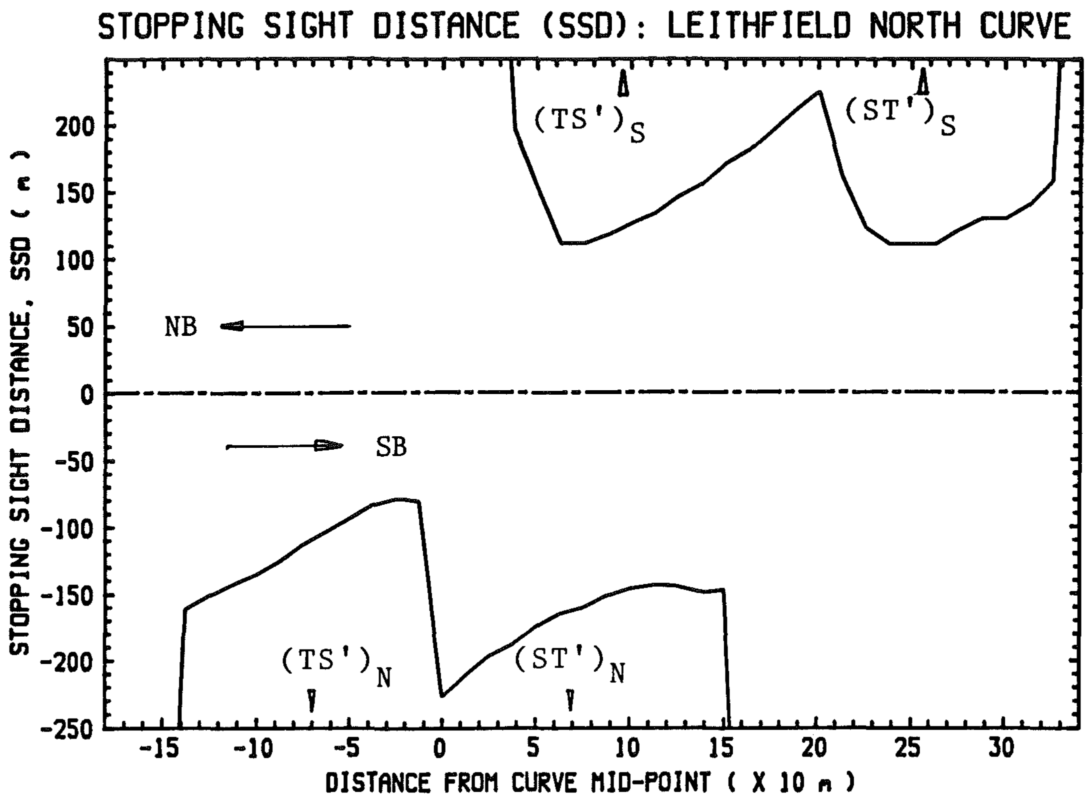

FIGURE 4.5

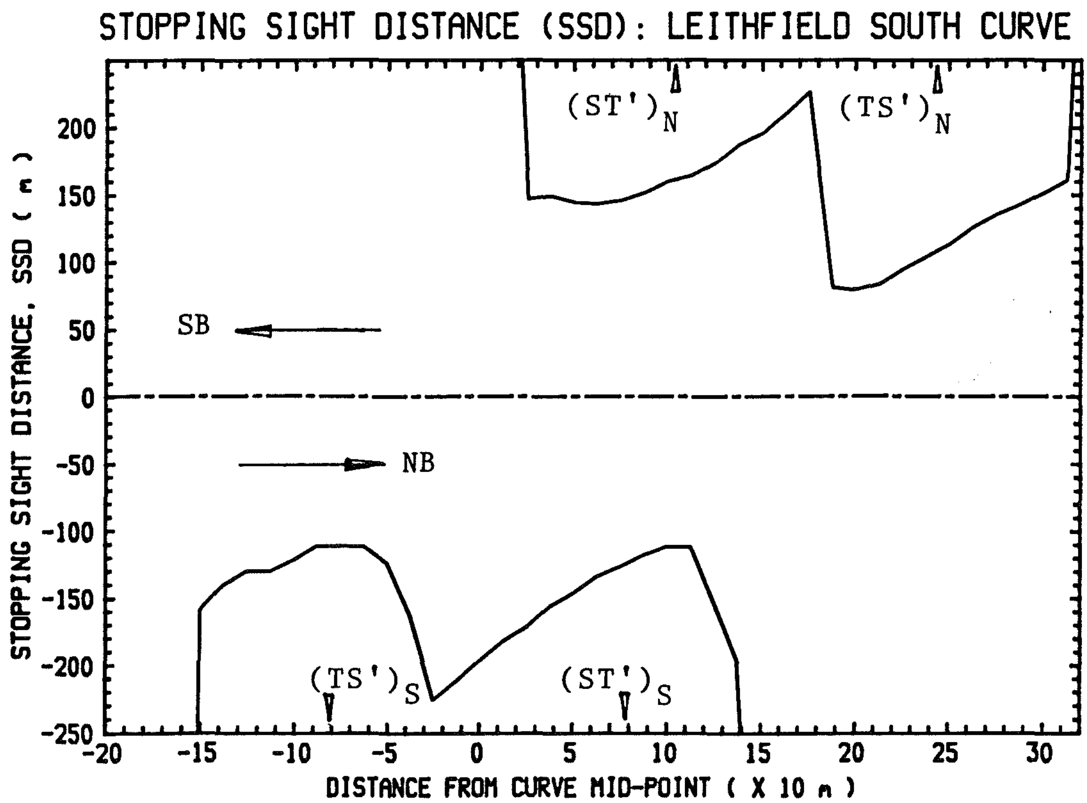

FIGURE 4.6

The curve mid-point at the centre-line is used as the origin for longitudinal measurement. The direction of distance increment was chosen to be the same as the vehicle flow direction on the inside curve (as for the Foremans Road curve). The centre-line at each control section is used as the origin for the lateral placement at that control section. Lateral placement was given a positive value if the vehicle reference point was on the same side of the road (with respect to the centre-line) as that designated for vehicle movement i.e. positive lateral placement if no centre-line encroachment. The vehicle reference points were the right front wheel (outer face) for the inside curves and the right rear wheel (outer face) for the outside curves.

4.2 DRIVER BEHAVIOUR DATA COLLECTION

Data were collected during day-light hours and in dry weather. There were four data collection periods, as shown in Table 4.2.

Case	Date/Day	Time
BS - N Curve (inside/outside)	1/8/86 (Fri.)	10.00 am - 4.00 pm
BS - S Curve (inside/outside)	31/7/86 (Thur.)	11.30 am - 4.00 pm
AS - N Curve (inside/outside)	12/12/86 (Fri.)	11.30 am - 4.00 pm
AS - S Curve (inside/outside)	16/12/86 (Tue.)	10.00 am - 3.00 pm

Table 4.2 Data Collection Period for Leithfield Reverse Curves

The hours of data collection were all within the week day time period when the proportion of drinking drivers is at its lowest. The traffic volume count data also indicate fairly uniform flow rates between the hours from 10 am to 4 pm for all week-days. The AS data collection was done 3 months after the completion of the curve re-alignment.

The data collection exercise yielded eight data sets (see Table 4.3). Within each data set, the data were further disaggregated into those for vehicles with opposing vehicular flow (WV) and without opposing vehicular flow (WOV) over a 'vicinity length'. For the BS curves, the 'vicinity lengths' were the lengths of the respective curves. The AS curves were much longer than the BS curves and the re-alignment had involved a considerable amount of levelling of the land adjacent to the roadway, resulting in loss of suitable vantage point to locate the video cameras to cover the full length of the AS curves. Data were collected for only 1/3 length of the AS-N curve and 3/4 length of the AS-S curve. The vicinity lengths for the AS curves were the lengths of the N curve and the length of the circular arc of the S curve. The sample sizes for the Leithfield study site are shown in Table 4.3.

Case		WV	WOV	Total
BS - N	: Inside	38	78	116
	: Outside	23	122	145
BS - S	: Inside	38	93	131
	: Outside	22	90	112
AS - N	: Inside	24	96	120
	: Outside	33	87	120
AS - S	: Inside	20	84	104
	: Outside	22	78	100

Table 4.3 Sample Sizes for Leithfield Study Site

The reduced data contained, for each vehicle, the speed and lateral placement values at each control section, as well as the vehicle wheel span (outer face to outer face), and whether there was or was not opposing vehicular flow in the vicinity. Only vehicles with wheel span between 1.2 m and 1.8 m were included for analysis (i.e. wide vehicles such as heavy trucks were excluded).

4.3 ANALYSIS OF DATA AND PRESENTATION OF RESULTS

The SAS statistical package was used for the analysis of the reduced data. Graphical plots were generated using the NCAR Graphical Package and plotted on a HP plotter.

Results are presented as profiles showing variation in driver characteristics along the curves as well as cumulative frequency distributions of driver behaviour characteristics at the mid-points of the curves. The same scales are used for the set of plots of each variable so as to allow easier comparison. The curve tangent-spiral and spiral-circular junctions (as shown in Figure 4.2) are marked on the top and/or bottom axes of the profile plots. The profile plots also show symbols of "triangle" and "plus sign" to indicate the position of control sections. The distance between adjacent pairs of "triangle" and adjacent pairs of "+'s" in the 'before' and 'after' profiles, respectively, are different because of the different distance between control sections in the BS and AS curves (12.5 m for the BS curves and 10.0 m for the AS curve).

Analysis was not done for the disaggregated WV and WOV data subsets. This was because of the variations in the definitions of vicinity length as well as the relatively small sample sizes for the WV subsets and the impression of considerable variations in behaviour. It was felt that it would be very hard to obtain statistical significance. The traffic flow at the Leithfield study site was approximately a third of the flow at Foremans Road curve (Compare Tables 3.1 and 4.1), and this lower flow allowed a high sampling rate to be obtained, since there were fewer vehicles in platoons.

4.4 BEHAVIOUR ALONG CURVES

The results for mean speed, lateral placement, centrality index and encroachment upon the delineation lines (i.e. centre-line and edge-line) are shown as profiles for each of the curves. Comparisons are made for inside and outside, North and South, and before and after curves. It should be noted that the data for each of the reverse curves were collected on separate days, and therefore the profile at each reverse curve should not be linked for joint analysis of the reverse curves as a single entity. In general, the results related mainly to the reverse curves and their approaches/departures. That is, the profiles show mainly the reverse curves and their approach and departure, with very little data on the common tangent (section between $(ST')_N$ and $(TS')_S$ in Figure 4.2). It should be noted at this stage that the inside curve is also the first curve encountered after a long tangent while the outside curve is the follow-on curve after the driver has gone through the inside curve. Therefore, variations in behaviour between the inside and outside curves may be due to (1) their being inside and outside curves (See Foremans Road Curve results), (2) their being first and second curves respectively.

4.4.1 Mean Speed Profiles

The mean speed profiles for each of the study curves i.e. BS-N, BS-S and AS-N, AS-S are presented in the following sections. The trends in the mean speed profiles are discussed, and regions of minimum mean speed are identified. Comparisons are made between the inside and outside of each study curve.

4.4.1.1 Mean Speed Profile on Before-Study North (BS-N) Curve

The mean speed profile (See Figure 4.7) on the inside curve (i.e. for south-bound traffic), exhibits a consistent steep reduction in mean speed along the

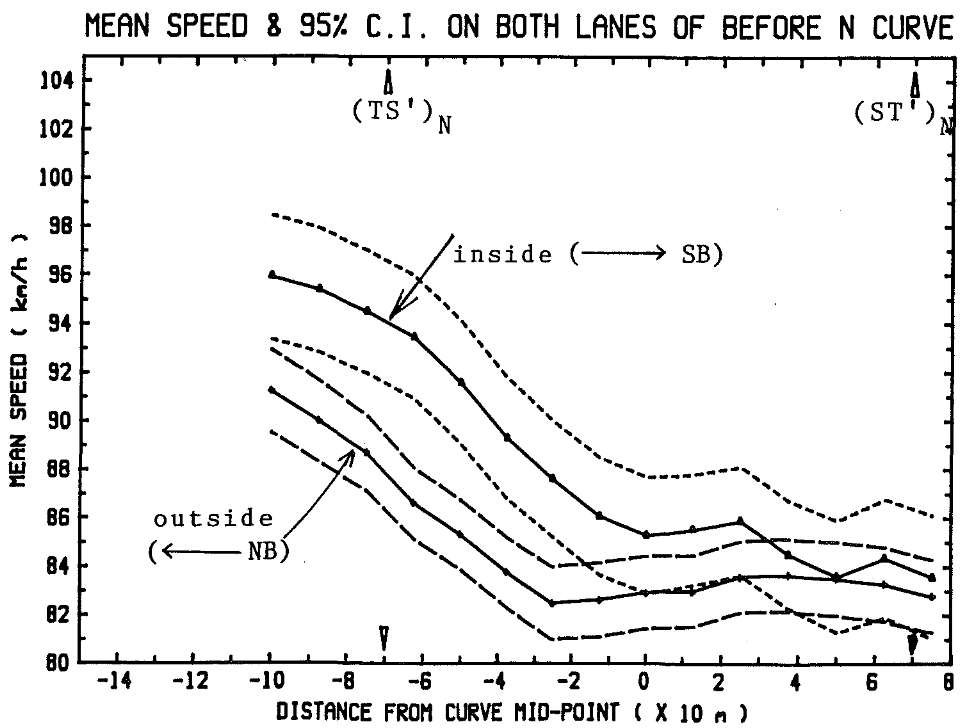

FIGURE 4.7

approach half of the curve with a deceleration of 0.85 m/s/s and a moderate double rise-and-dip mean speed pattern on the remainder of the inside curve. The overall trend was a general speed reduction across the length of the inside curve. The mid-point of the curve, which marks the onset of the rise-and-dip pattern, is also the point of the curve at which the driver has maximum sight distance ahead (See Figure 4.5).

The outside curve mean speed profile shows a very moderate rise-and-dip of the mean speed from curve entry to a point 25 m after the mid-point of the curve (lower solid line in Figure 4.7). The moderate rise-and-dip profile indicates very little speed adjustment over this length of the curve. A steep increase in mean speed at an average acceleration of 0.78 m/s/s follows after the minimum mean speed.

The BS-N curve mean speed profiles show similar rates of acceleration and deceleration. The mean speed values for the curve near to the common (central) tangent are close to each other. The inside curve profile is noted for the lack of a distinct minimum mean speed within the curve. The fact that the point of minimum mean speed is 25 m after the mid-point of the outside curve is also worth noting. A comparison of the confidence interval bands (shown as dashed lines) shows a smaller band for the outside curve (i.e. less variablility in the speed of north-bound traffic).

4.4.1.2 Mean Speed Profile on Before-Study South (BS-S) Curve

The mean speed profile for the inside curve (i.e. for north-bound traffic), is characterized by an initial strong deceleration followed by a fairly flat trough and then a moderate increase in mean speed thereafter (lower solid line in Figure 4.8). The deceleration in the first 50 m was just over 1 m/s/s. The flat trough indicates constant mean speed from 37.5 m to 12.5 m before the mid-point of the curve. The bottoming of the profile also coincides with the point of the curve at which the driver has maximum sight distance ahead (see Figure 4.6). A moderate acceleration of 0.28 m/s/s follows the region of minimum mean speed.

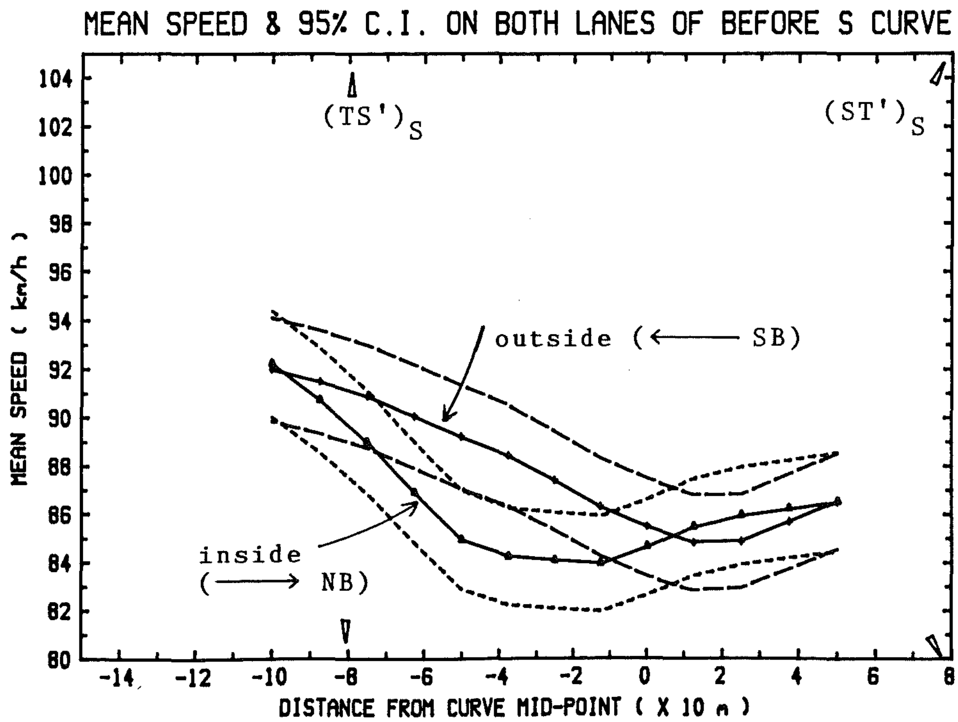

FIGURE 4.8

The mean speed profile for the outside curve shows a uniform speed reduction at a deceleration of 0.45 m/s/s over the first 25 m to reach a minimum mean speed 20 m before the curve mid-point (upper solid line in Figure 4.8). This point of minimum mean speed is also the point of the curve at which the driver can see far ahead (> 250 m) into the adjoining tangent section (See Figure 4.6). The profile beyond the minimum mean speed exhibits a mirror image of the speed reduction but at a slightly lower rate of acceleration of 0.44 m/s/s; this acceleration is maintained for the rest of the departure.

The profiles on the inside and the outside curves indicate generally different acceleration patterns and regions of minimum mean speed. However, the rates of acceleration/deceleration and the mean speed for the two directions in the vicinity of the common (central) tangent have very similar values.

4.4.1.3 Mean Speed Profile on After-Study North (AS-N) Curve

Data were collected for only a short section of the AS-N curve as there was no suitable vantage point to locate the video cameras to cover a greater length of the curve. The mean speed profile (Figure 4.9) on the inside curve shows a moderate speed reduction, at a deceleration of 0.43 m/s/s, over the first quarter of the circular arc, and a fairly constant mean speed over the remainder of the observed section (upper solid line). The mean speed profile for the outside curve, as shown by the lower solid line in Figure 4.9, shows a very gradual mean speed increase over the departure half of the circular arc. The inside and outside profiles generally show similar trends in acceleration/deceleration and statistically insignificant differences in the mean speed values (at the 95% confidence level).

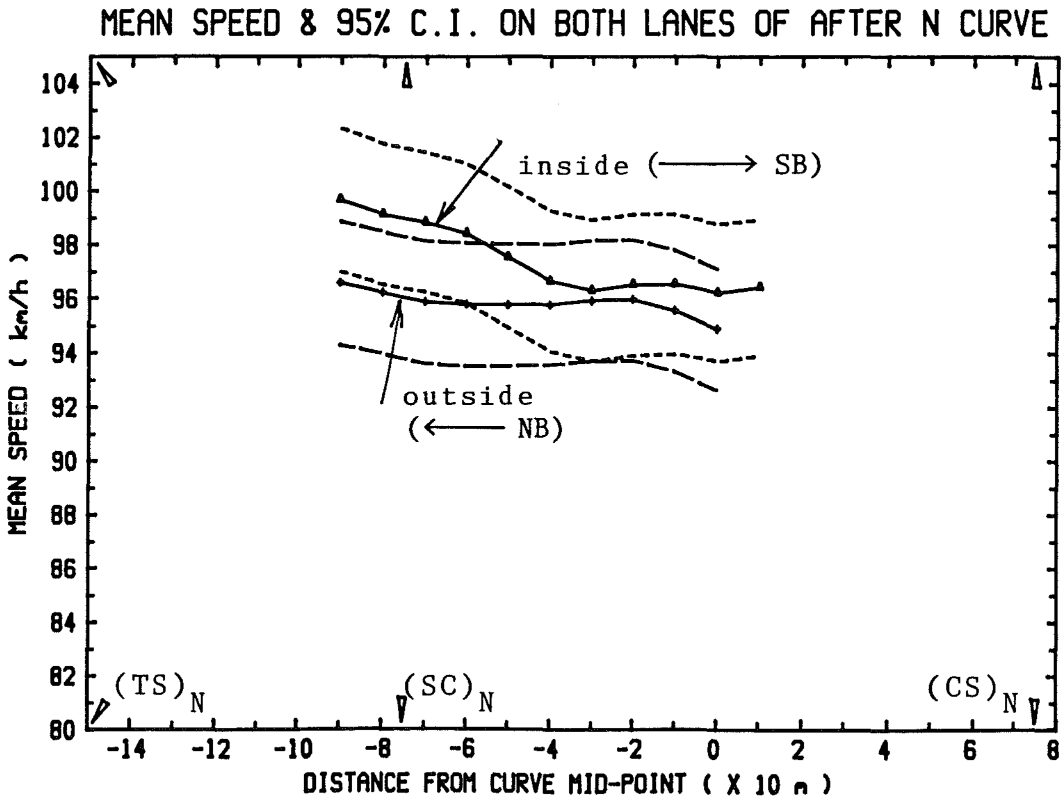

FIGURE 4.9

4.4.1.4 Mean Speed Profile on After-Study South (AS-S) Curve

The inside mean speed profile (Figure 4.10) on the AS-S curve exhibits a very gradual speed decrease along the length of the approach half of the curve, at a moderate deceleration of 0.165 m/s/s (lower solid line). There is a distinct minimum mean speed at the mid-point of the curve, which is followed by quite a rapid speed increase with an acceleration of nearly 0.3 m/s/s.

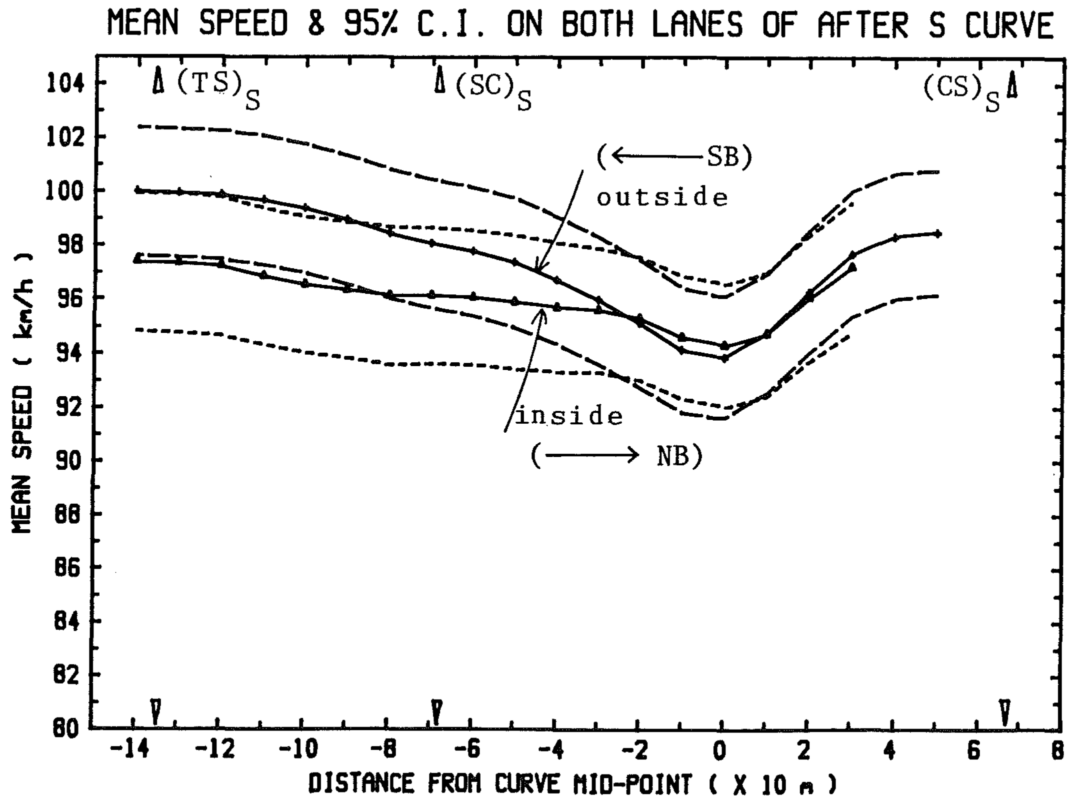

FIGURE 4.10

The mean speed profile for the outside curve shows almost identical mean speed values in the vicinity of the mid-point of the curve (upper solid line in Figure 4.10). A fairly strong increase in the mean speed extends across the length of the departure half of the outside curve. In general, the inside and outside profiles show very similar patterns of acceleration/deceleration. The differences in the mean speed values over the length of the curve are also statistically insignificant at the 95% confidence level.

4.4.1.5 Comparison of the Mean Speed Profiles on the Inside and Outside Lanes of the Curves

The mean speed profiles as discussed above (See 4.4.1.1 to 4.4.1.4) show that:

(a) the mean speed is not constant throughout the circular curves;

(b) the acceleration and deceleration patterns are different on the inside and outside lanes of the same curve; the AS-S mean speed profile shows an apparently similar rate of speed adjustment in the vicinity of the mid-point of the curve;

(c) the rate of speed adjustment on the inside and outside lane of the same curve shows a greater similarity on the half of the curve nearer to the middle of the reverse curves;

(d) the rate of speed adjustment is greater on the half of the curve nearer to the ends of the reverse curves than on the other half, on the BS curves; this trend is reversed for the AS-S curve.

4.4.2 Comparison of Mean Speed Profiles on the Before-Study and After-Study Curves

The mean speed profiles for the before-study and after-study curves are presented in Figures 4.11 - 4.14. The trends in each individual profile, as well as variations between the inside and outside lanes of the same curve, have been discussed in section 4.4.1 above. The emphasis in this section is on the differences in the mean speed profiles as a result of the re-alignment work.

The profiles in Figures 4.11 - 4.14 show that:

(a) the mean speed values in the BS curves are substantially and statistically significantly less than for the AS curves, throughout the complete length of the curves;

MEAN SPEED PROFILE & 95% C.I. ON INSIDE OF B.& A. N CURVES

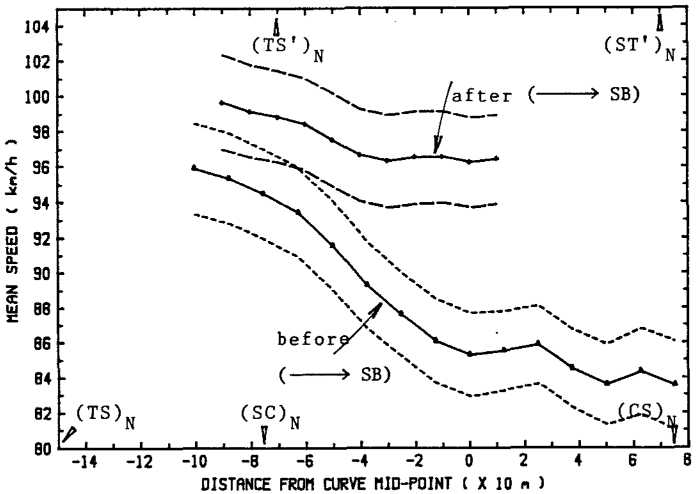

FIGURE 4.11

MEAN SPEED PROFILE & 95% C.I. ON OUTSIDE OF B.& A. N CURVES

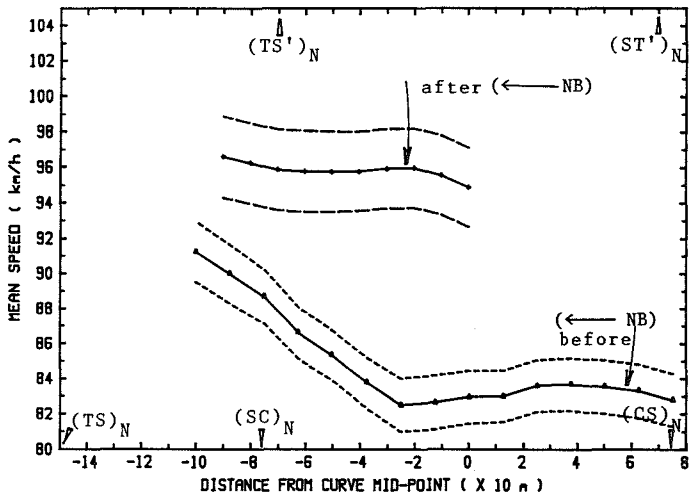

FIGURE 4.12

MEAN SPEED PROFILE & 95% C.I. ON INSIDE OF B.& A. S CURVES

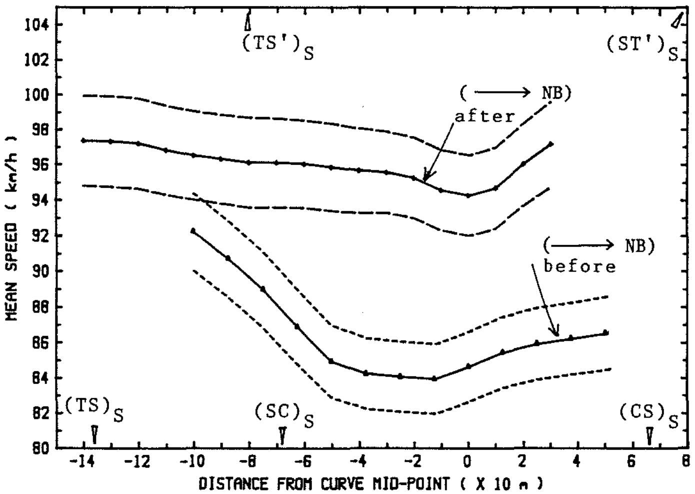

FIGURE 4.13

MEAN SPEED PROFILE & 95% C.I. ON OUTSIDE OF B.& A. S CURVES

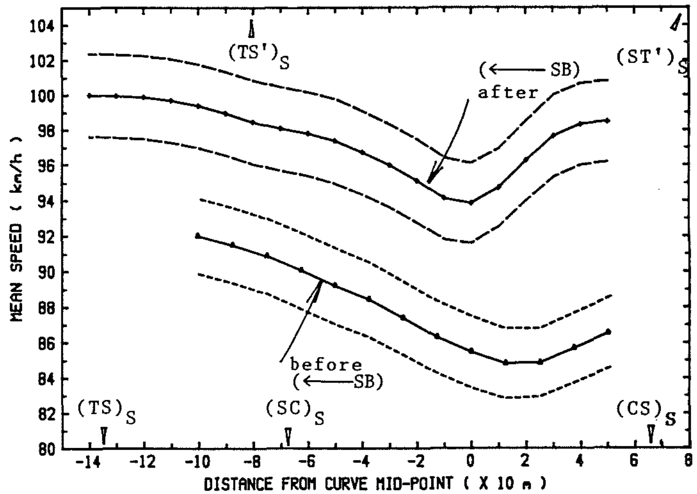

FIGURE 4.14

(b) the rate of acceleration and deceleration for the BS curves on the half of the curves adjoining the long tangents are noticeably greater than for the AS curve's, with the exception of the outside lane of the S curve for which there were very similar rates of acceleration;

(c) the rate of acceleration and deceleration for the BS curves on the half of the curves nearer to the middle of the reverse curves is less than for the AS-S curve (there was insufficient data for the AS-N curve);

(d) the AS profiles exhibit minimum mean speed at the mid-points of the respective curves, while the minimum mean speed in the BS profiles is offset to a position before the curve mid-point (driver's perspective) in the BS-S curve and after the curve mid-point in the BS-N curve.

4.4.3 Comparison of Mean Speed Profiles on the N and S Curves

Mean speed profiles are presented in Figures 4.15 - 4.18 for making comparisons between the inside-N and the inside-S curves and between the outside-N and the outside-S curves.

4.4.3.1 Mean Speed Profiles on the Inside of BS-N and BS-S Curves.

The mean speed profiles in the BS-N and BS-S curves (solid lines in Figure 4.15) both show a similar initial rate of deceleration. However, the BS-N profile displays a trough followed by minor rises and dips, while the BS-S profile displays a trough followed by a region of consistent speed increase.

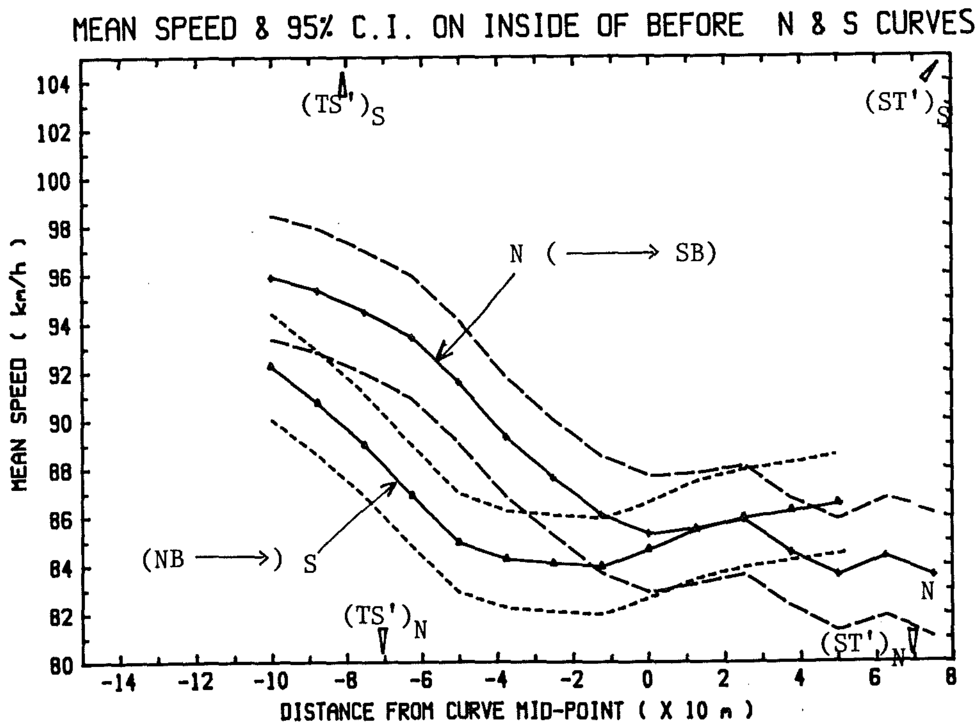

FIGURE 4.15

The large initial drop in speed reflects speed adjustment while progressing through the curve with decreasing radius. The driver's view of the curve ahead at the point of curve entry is shown in Plate 4.1 (for a south-bound driver entering the N curve) and in

Plate 4.1 Looking south from curve entry of N Curve

Plate 4.2 Looking north from curve entry of S Curve

Plate 4.2 (for a north-bound driver entering the S curve). At this point, the driver cannot see the follow-on curve ahead.

Considering the profile of the BS-N curve, the first trough at the mid-point of the curve is probably because the point of minimum radius has been reached. The first trough also coincides with the point at which the driver has maximum sight distance (Figure 4.4) and the driver can see ahead to the follow-on curve. The driver view at this point is as shown in Plate 4.3. It is suggested that the increasing curve radius after the curve mid-point and the driver's perception of the follow-on curve has interacted to produce the minor rise-and-dip pattern in the mean speed profile.

The BS-S curve mean speed profile displays a trough between 37.5 m to 12.5 m ahead of the curve mid-point. The trough region is also the point in which the driver's has maximum sight distance ahead (Figure 4.5). The driver view at the mid-point of the S curve is shown in Plate 4.4. It is suggested that the moderate but continual rise in mean speed could be due to drivers not having fully perceived a fairly tight curve ahead. Comparing Plates 4.3 and 4.4, it seems likely that the driver can perceive, during daylight hours, the S curve in Plate 4.3 better than the N curve in Plate 4.4 since the S curve has less obstruction on the inside of the curve as well as a 'wall' of bush on the outside of the curve.

Plate 4.3 Looking south from curve mid-point of N Curve

Plate 4.4 Looking north from curve mid-point of S Curve

4.4.3.2 Mean Speed Profiles on the Outside of BS-N and BS-S Curves

The mean speed profiles on the outside curves are characterized by a moderate speed reduction followed by a moderate speed increase for the S curve, and a minor rise-and-dip followed by a very sharp rise in mean speed for the N curve (solid lines in Figure 4.16)

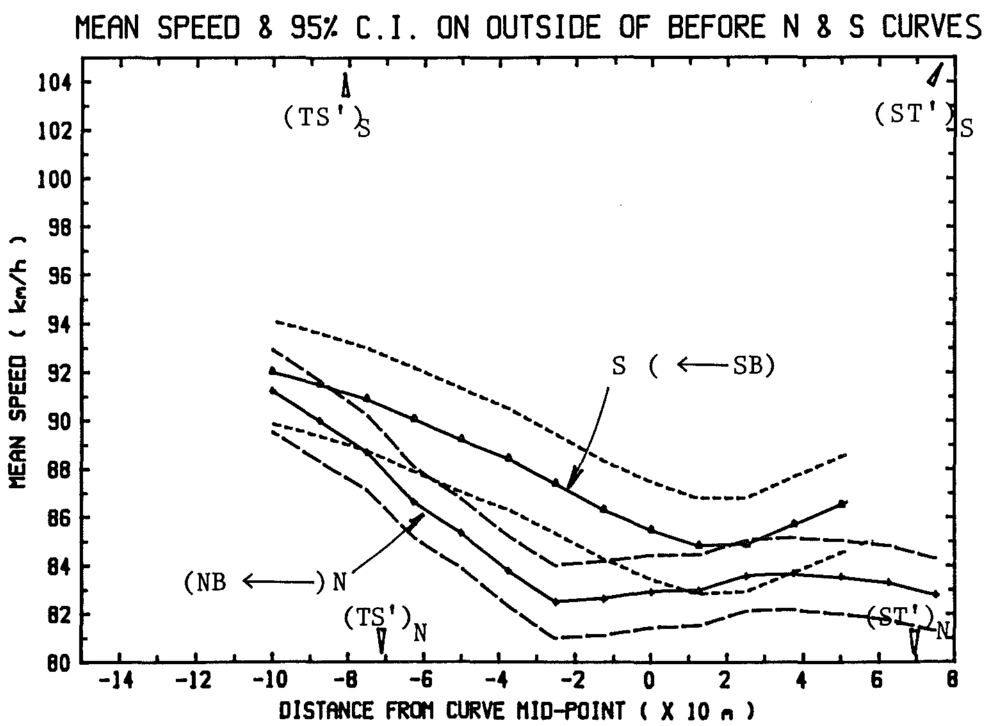

FIGURE 4.16

The initial reduction in speed in the S curve is probably related to the driver responding to the perception of the tight curve ahead. The driver view at the curve entry point is as shown in Plate 4.5.

Plate 4.5 Looking south from curve entry point of S Curve

Plate 4.6 Looking north from curve entry point of N Curve

Minimum mean speed occurs at a point 20 m before the mid-point of the curve and this is also the point at which the driver can see far ahead into the long tangent (Figure 4.5).

The notable feature of the N curve is the minimal speed adjustment from curve entry to 25 m after the mid-point of the N curve. The driver view at the point of curve entry is as shown in Plate 4.6. Comparing Plates 4.5 and 4.6, it is likely that the south-bound driver can see further ahead since there is less obstruction on the inside of the S curve. The field survey of stopping sight distance (See Figures 4.4 and 4.5) has shown that the minimum SSD for the S curve is 39% more than that of the N curve (143 m and 110 m respectively). It is suggested that the greater obstruction on the inside of the N curve has influenceed the perception of the N curve by the driver and has accordingly contributed to the 'delayed' acceleration. SEE ERRATA

4.4.3.3 <u>Speed Behaviour at Location of Minimum Stopping Sight Distance</u>

The preceding two sections has dealt with the probable influence of the driver's view of the curve ahead on the speed behaviour, in an attempt to explain the different mean speed profiles for the inside and outside lanes of the North and South curves. The stopping sight distance profiles have been used mainly to locate the positions of maximum sight distance (i.e. the positions at which the follow-on curve or adjoining long tangent comes into driver's view). The speed behaviour is further examined at the locations of minimum stopping sight distance (SSD) of the BS curves. There is no SSD restriction at the AS curves.

In the design of horizontal curve, provision for drivers to stop in response to a road hazard ahead is catered for by providing adequate SSD. This SSD is the 'safe stopping sight distance' or SSSD at that design speed. Alternatively, an equivalent design speed (EDS) can be specified for a given SSD. The SSSD for the BS curves at the advisory speed of 70 km/h is equivalent to 85 m (Table 5.2, NAASRA 1980). The minimum SSD measured at the BS curves were as shown in Table 4.4.

Case	Min. SSD (m)	EDS (km/h)	Prop. (%) > EDS	Actual Mean Speed (km/h)
Inside - N (25 m before M.P.)	79	68	96.6	87.6
Inside - S (75 m before M.P.)	110	82	73.3	88.9
Outside - N (75 m before M.P.)	111	82	51.0	87.4
Outside - S (63 m before M.P.)	143	93	33.9	82.8

Table 4.4 Speed Behaviour at Locations of Minimum Stopping Sight Distance

The above figures indicate that a high proportion of the subject vehicles exceeded the equivalent design speed for the measured minimum SSD. It should be noted that the proportions are highest for the inside curves which are also the first of the reverse curves. It can therefore be argued that the higher proportions are due to (a) their being the inside curves, (b) their being the first of the reverse curves. It is not possible to separate the effect of the attributes (a) and (b) on the speed behaviour at minimum SSD. The proportions of vehicles exceeding the EDS suggest that the N-curve was likely to be more hazardous than the S-curve (in their respective lanes) in terms of incidents that involved responding to hazards on the road ahead. It is interesting to note that the inside lane of the N-curve had both the highest proportion and the highest incidence of accident occurrence (See Section 4.6 later). It is also noted that the actual mean speed is apparently not influenced by the large differences in the SSD (i.e. minimum SSD is a poor predictor of actual speed behaviour). The high proportions of vehicles exceeding the equivalent design speed for minimum SSD at all the BS curves suggest that maintaining a speed to allow an adequate SSD is probably of secondary importance to the driver.

4.4.3.4 Mean Speed Profiles on the Inside of AS-N and AS-S Curves

The mean speed profiles on the inside of the AS-N curve and the AS-S curves shown similar trends (solid lines in Figure 4.17). The profile for the AS-S curve displays a moderate rate of speed reduction followed by a relatively large rate of speed increase.

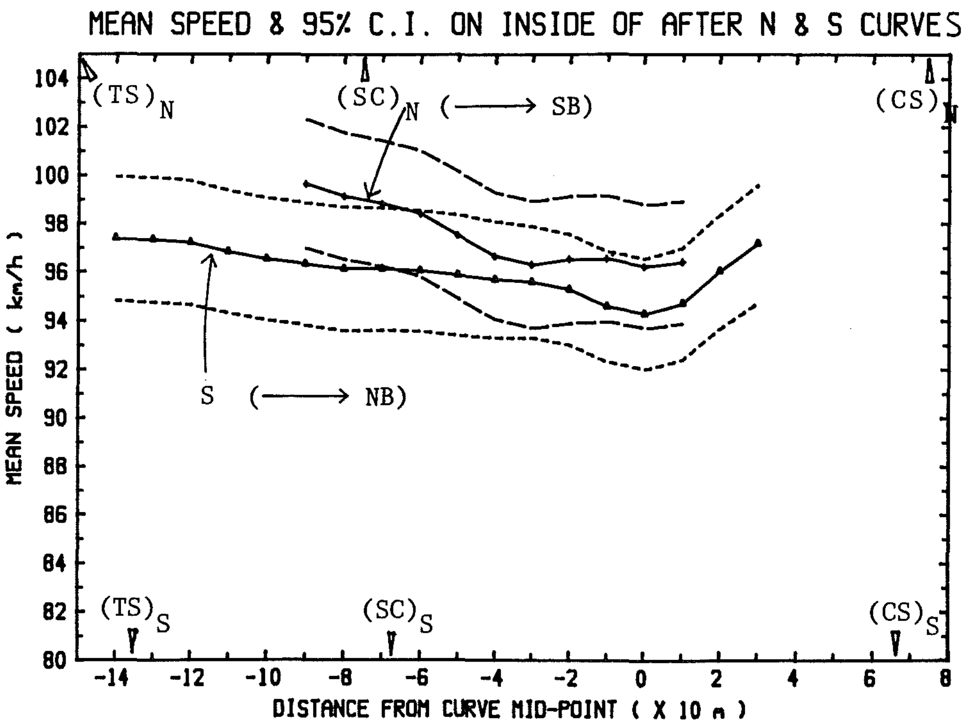

FIGURE 4.17

This shows drivers going through the first half of the curve at a slow, steady rate of deceleration (a desirable behaviour). The profile for the AS-N curve is limited to 1/3 the length of the curve and no further conclusion is drawn regarding its mean speed profile.

4.4.3.5 Mean Speed Profile on the Outside of AS-N and AS-S Curves

As the mean speed profile for the AS-N curve is rather restricted, only the profile for the AS-S curve is considered. The AS-S profile displays a region of moderate deceleration, with minimum mean speed at the mid-point of the curve (solid lines in Figure 4.18). A moderate acceleration extends from the point of minimum speed across the length of the departure curve. It is not clear why the rate of deceleration on the approach half of the curve is greater than the acceleration on the departure half of the curve.

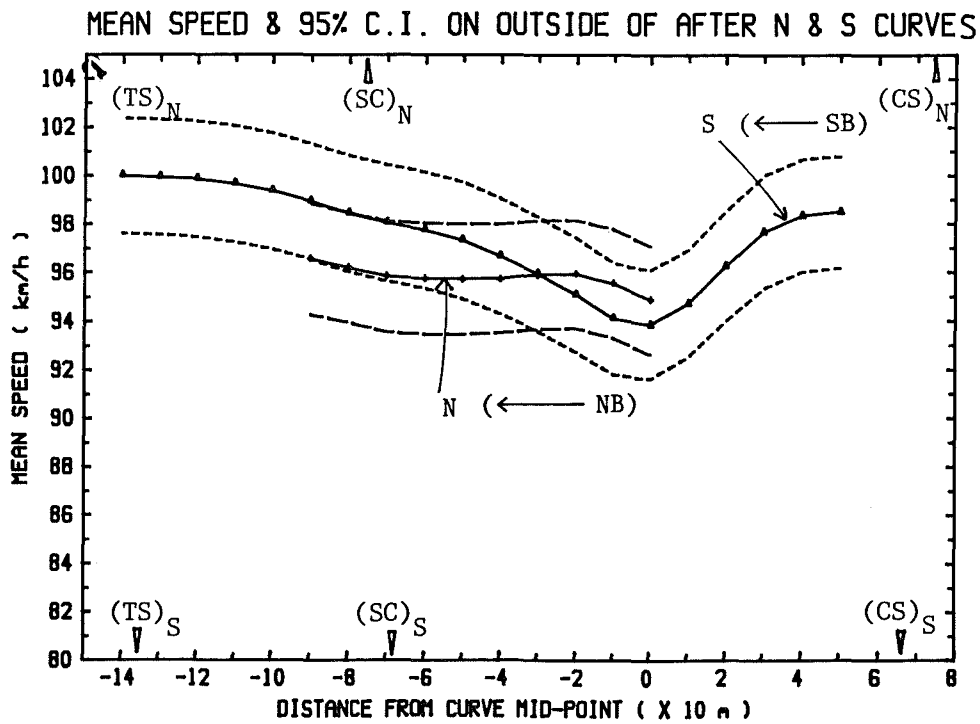

FIGURE 4.18

4.4.4 Mean Speed Behaviour in the Central Region of the Reverse Curves

The mean speed behaviour on both the N and S curves has been discussed in the preceding sections. The limitations of the data collection equipment have resulted in a section of the central region of the reverse curves not being observed. Furthermore, data for the N and S curves were collected on different days, hence the results for the curves are obtained from different samples. A combined plot of the N and S curves mean speed profiles are presented in Figures 4.19-4.22 to give an indication of the possible mean speed behaviour in the central region.

The combined plot for the BS curves are as shown in Figures 4.19 and 4.20, where the length of the unobserved section is 63 m. On the assumption that the samples for the N and S curves are both representative (on account of the quite large sample sizes as well as the same hours for the data collection and the care taken in obtaining the data sets), the speed profiles of the N and S are expected to converge as shown by the dashed lines. If this was the case, then an average south-bound driver leaving the N curve would require an average acceleration of 0.4 m/s/s to 'connect' to the entry mean speed for the S curve (dashed line in Figure 4.19), while an average north-bound driver leaving the S curve would require an average deceleration of 0.5 m/s/s to 'connect' to the entry mean speed of the N

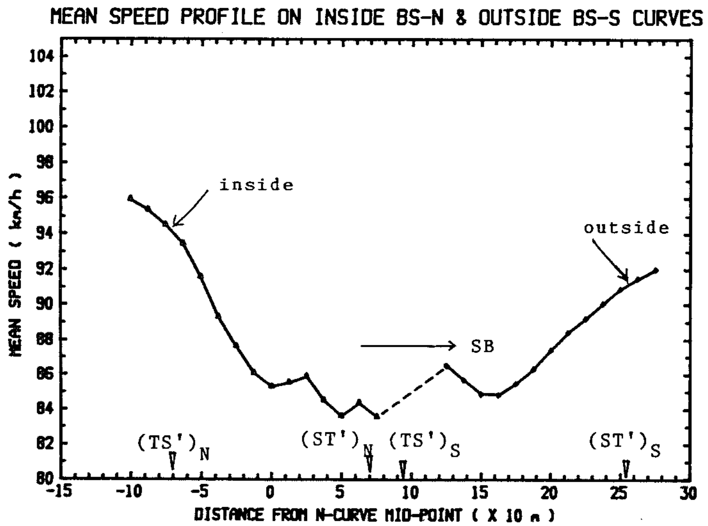

FIGURE 4.19

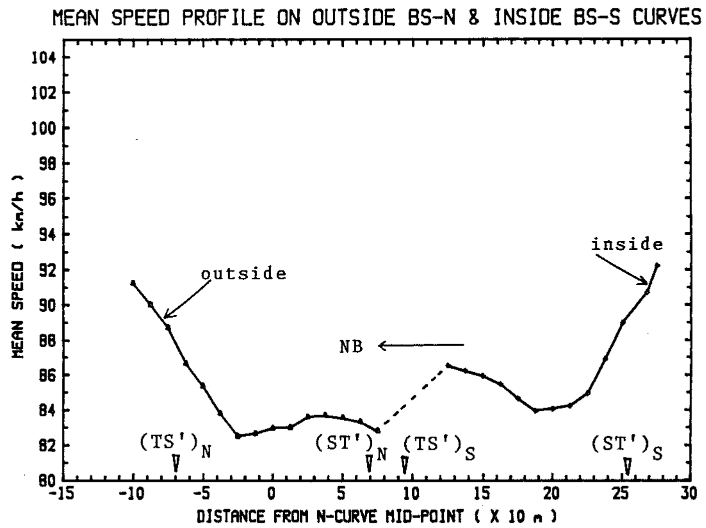

FIGURE 4.20

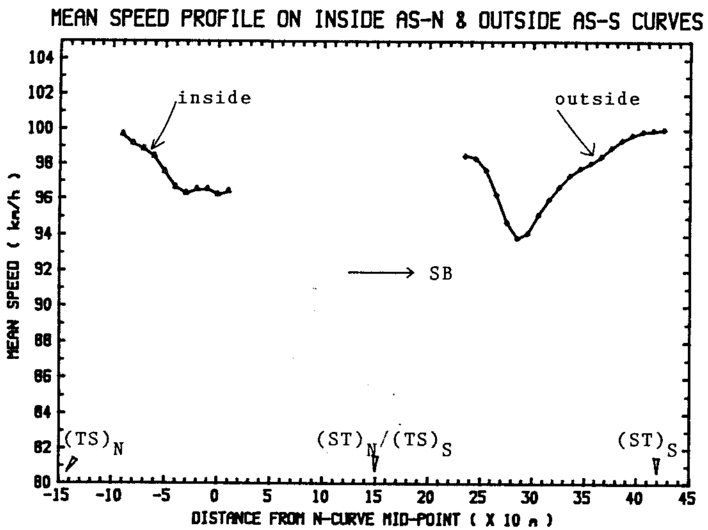

FIGURE 4.21

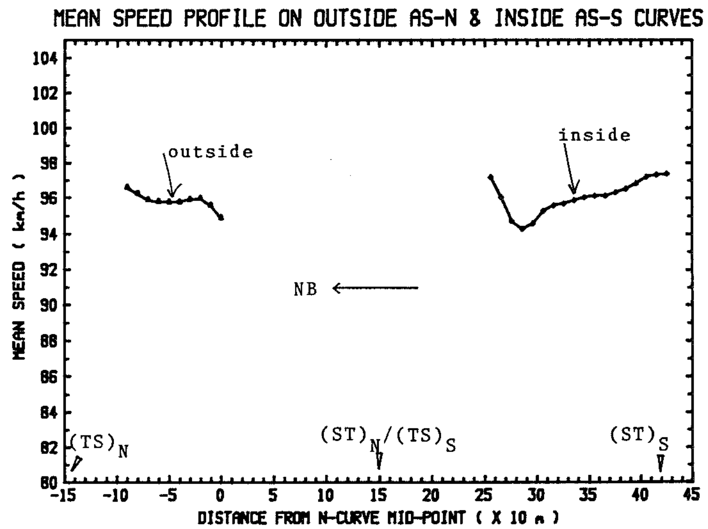

FIGURE 4.22

curve (dashed line in Figure 4.20). This speed behaviour is within the practical acceleration and deceleration limits, and is not inconsistent with the idea that south-bound drivers have a better perception of the follow on-curve than north-bound drivers, as discussed in sections 4.4.3.1 and 4.4.3.2. The actual speed behaviour of individual drivers could however have been very different from the scenario as presented above. The length of the unobserved central section of the AS curves is very large (Figures 4.21, 4.22). It is therefore not possible to draw any meaningful conclusion from the combined plots of the AS N and S curves.

4.4.5 Mean Lateral Placement

The mean lateral placement (MLP) profiles for each of the curves are presented in the following sections. The trends in the profiles are discussed, and comparisons are made between the inside and the outside of each curve. The mean lateral placement on the inside curves are, for presentation purpose, plotted on a negative scale. With the profiles plotted on positive and negative scales, the lateral separation between the reference wheels on the inside and outside curves is represented by the vertical interval between the inside and outside profiles. The curve centre-line is represented by the line of zero MLP.

4.4.5.1 Mean Lateral Placement on Before-Study North Curve

The MLP profile for the inside curve (lower solid line in Figure 4.23) shows a strong shift away from the centre-line from 40 m before curve entry and reaching a maximum MLP at 12.5 m before the curve mid-point. This is followed by a gradual shift towards the centre-line along the remainder of the curve.

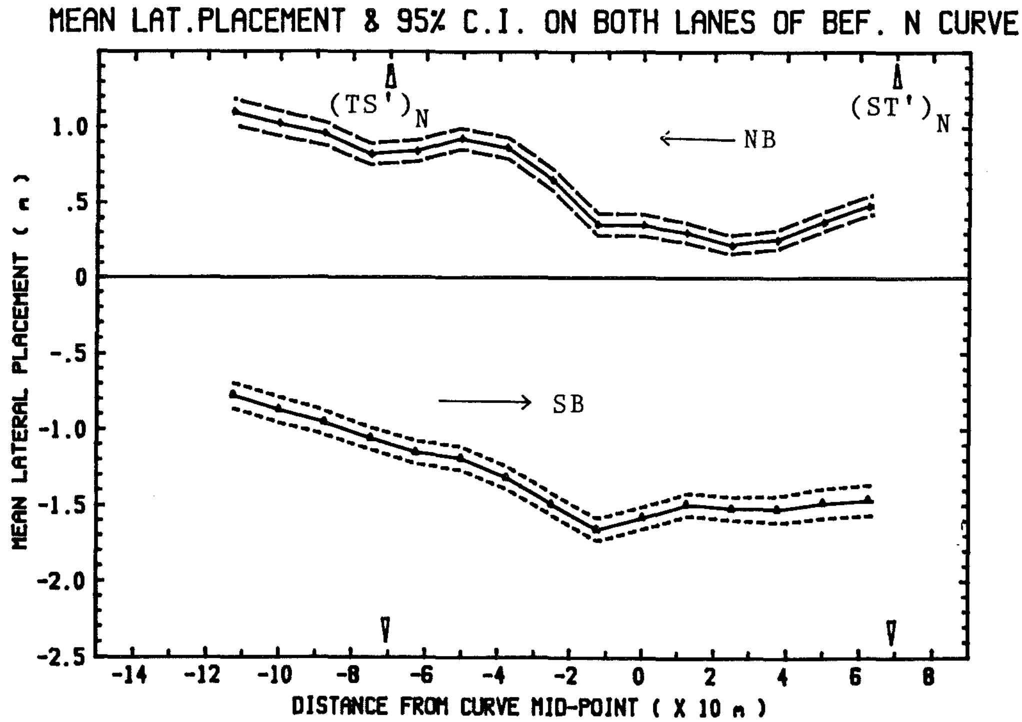

FIGURE 4.23

The MLP profile for the outside curve (upper solid line in Figure 4.23) exhibits a shift towards the centre-line for the first 40 m. This is followed by movement away from the centre-line along the rest of the road section except for a 'recovery' region in the vicinity of the curve departure point.

Comparing the MLP profiles with stopping sight distance profiles (See Figure 4.5), it is noted that the maximum MLP for the inside curve occurs close to the point at which SSD is a maximum for the inside curve. The minimum MLP on the outside curve also occurs close to the point at which the SSD restriction ends.

Comparing MLP profiles with roadway width (see Figure 4.3), there seems to be no apparent relationship between roadway width and the MLP for the inside curve. For the outside curve, the variation in the sealed shoulder width seems to have some influence on the MLP profile, noting that the commencement of strong movement away from the centre-line is also the point at which roadway width was minimum, while the 'recovery region' is centered at another minimum roadway width.

Comparing the MLP profiles with the mean speed profiles (see Figure 4.7), the larger rates of change of MLP coincide with the larger rates of change of mean speed while the smaller rates of change of MLP coincide with the smaller rates of change of mean speed. That is, variation in lateral placement is correlated with variation in speed.

The MLP profiles indicate larger changes in the MLP on the half of the curve nearer to the north end of the reverse curve. The lateral separation between the inside and outside profile varies between 1.75 m and 2.2 m; the lateral separation at the curve mid-point and the north curve entry point are both 1.9 m.

4.4.5.2 Mean Lateral Placement on Before-Study South Curve

The MLP for the inside curve (lower solid line in Figure 4.24) shows a slight shift towards the centre-line in the region before curve entry, followed by strong movement away from the centre-line. The maximum MLP from the centre-line occurs at 12.5 m before the curve mid-point and this is followed by a gradually increasing rate of shift towards the centre-line for the remainder of the curve, with signs of a levelling-off near to the end of the curve.

The MLP for the outside curve (upper solid line in Figure 4.24) shows initially a strong shift towards the centre-line with a minimum MLP at 25 m past the curve mid-point (i.e. two third of the way through the outside curve). This is followed by strong shift away from the centre-line for the remainder of the curve, with some evidence of a levelling off of the MLP at the departure of the curve.

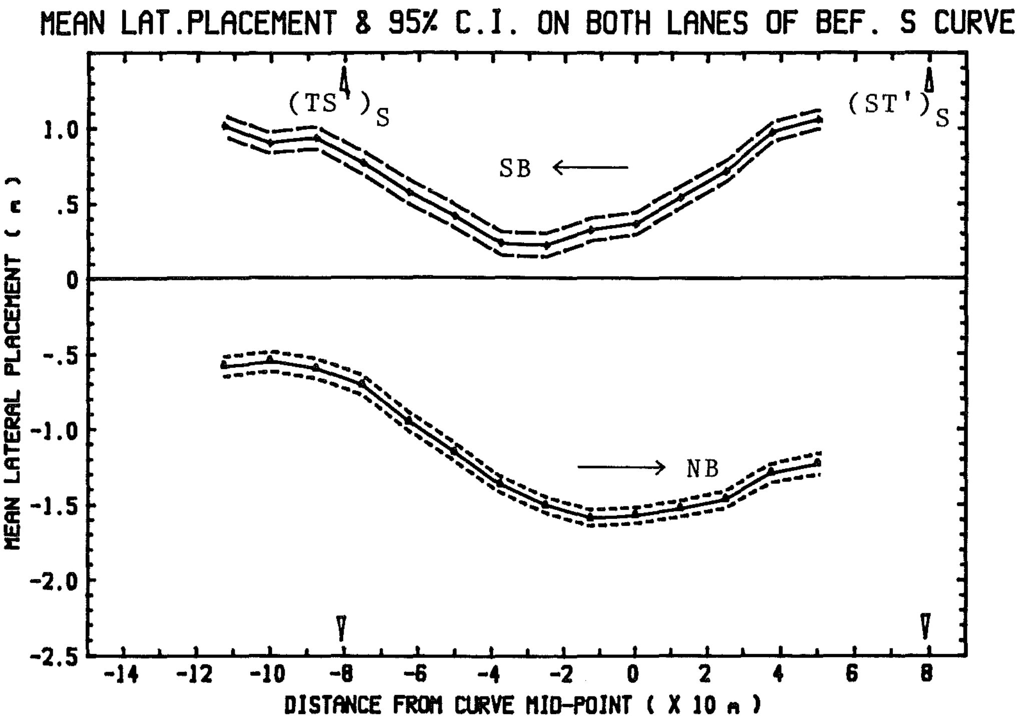

FIGURE 4.24

Comparing the MLP profiles with the SSD profiles (See Figure 4.6), the maximum MLP for the inside curve occurs close to the point at which the inside curve SSD is a maximum. The minimum MLP for the outside curve occurs nearly 50 m after the end of the SSD restriction.

Comparing the MLP profiles with roadway width (See Figure 4.4), no simple relationship is evident. However, the reduction of roadway width at the departure region of the outside curve coincides with the levelling-off of the MLP for the outside curve.

Comparing the MLP profiles with the mean speed profiles (See Figure 4.8), the inside curve shows that the shift away from the centre-line is accompanied by a drop in the mean speed. The minimum mean speed also coincides with the maximum mean MLP. The MLP profile for the outside curve indicates no correlation with the mean speed.

The lateral separation between the inside and outside profiles varies from 1.5 m in the vicinity of the south entry point and increases progressively towards the north end of the curve. The lateral separation at the curve mid-point is 1.9 m, and increases to 2.3 m near to the north end of the curve.

4.4.5.3 Mean Lateral Placement on After-Study North Curve

The MLP profile for the inside curve (lower solid line in Figure 4.25) shows a fairly strong shift away from the centre-line for the first 50 m of the observed section and then a minimal change in the MLP along the remainder of the section. The MLP for the outside curve (upper solid line in Figure 4.25) exhibits a very shallow concave profile, with the minimum MLP at a point 60 m past the curve mid-point. Comparison of the MLP profiles with roadway width profiles (See Figure 4.3) and mean speed profiles (See Figure 4.9) does not show any simple relationship between MLP and roadway width or mean speed. The

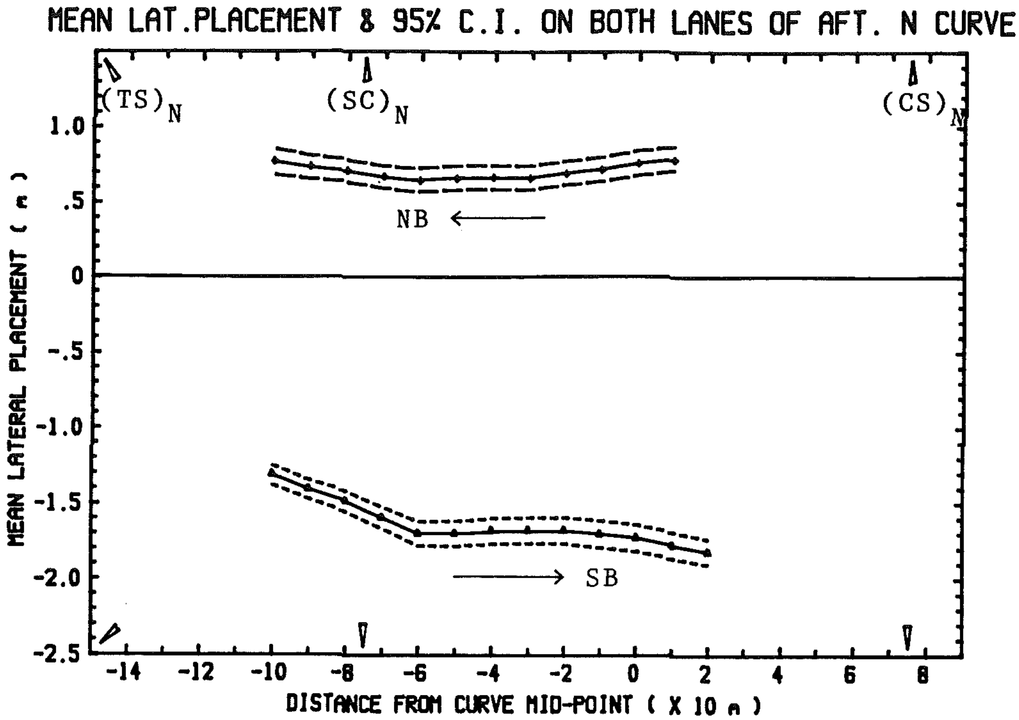

FIGURE 4.25

lateral separation between the inside and outside profiles varies from 2.25 m at the north spiral-circular point to 2.5 m at the curve mid-point.

4.4.5.4 Mean Lateral Placement on After-Study South Curve

The MLP profile for the inside of the AS-S curve shows movement away from centre-line from before curve entry and all the way past the spiral-circular point, with a 'recovery' along the circular curve before the curve mid-point (lower solid line in Figure 4.26). This is followed by a further movement away from the centre-line and another 'recovery' commencing 20 m past the curve mid-point.

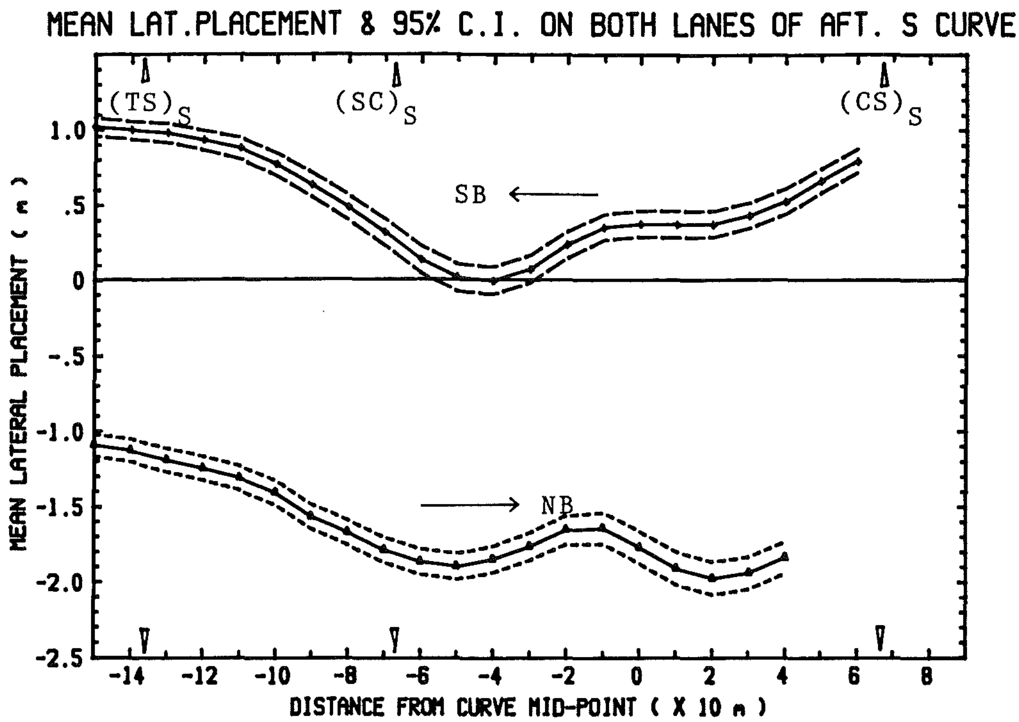

FIGURE 4.26

The MLP profile for the outside curve shows movement towards the centre-line, initially fairly strong then levelling off, followed by further strong movement towards the centre-line, to reach a minimum MLP near to the departure circular-spiral region (upper solid line in Figure 4.26). A strong shift away from the centre-line occurs along the remainder of the curve. The variation in the sealed shoulder width at the curve departure region (Figure 4.4) seems not to have affected the MLP profile.

Comparing the MLP profiles with the roadway width (See Figure 4.4) and mean speed profiles (See

Figure 4.10), there seems to be no apparent relationship between MLP and roadway width or mean speed. The lateral separation varies between 1.8 m and 2.4 m. The lateral separation at the south entry point, spiral-circular point and curve mid-point are 2.2 m, 2.1 m and 2.15 m respectively.

4.4.5.5 <u>Comparison of Mean Lateral Placement Profiles for the Inside and Outside Lanes of the Curves</u>

The profiles of the MLP as described in section 4.4.5.1 - 4.4.5.4 also show that:

(a) The MLP profiles for each curve is different from the others, though there seems to be some similarities in the trend of the MLP profiles between the inside and outside lanes of each curve.

(b) The relationship between the MLP profile and SSD profile is not clear. The maximum MLP for the BS inside curves seem to occur close to the maximum SSD.

(c) The MLP profiles for the before curves seem to be influenced by points of minimum roadway width.

(d) There is no simple relationship between the MLP and the mean speed. Movement towards the centre of the curve (towards and away from the centre-line for the outside and inside curves, respectively) seems to be generally (but not always) associated with a drop in the mean speed, and movement away from the centre of the curve associated with an increase in the mean speed.

(e) The MLP in the vicinity of the curve departure point on the outside of the BS curve shows evidence of 'correction' in the MLP.

(f) The MLP indicates that, in general, there is very little evidence of the wheel path radius being equal or nearly equal to the centre-line radius, as indicated by the absence of horizontal MLP profiles. Corner-cutting seems to be prevalent for the BS curves and the AS-S curve.

(g) The variance in the MLP for each of the profiles is fairly constant along the length of the observed section; the 95% confidence limits are similarly uniform for all MLP profiles.

(h) Lateral separation values for the inside and outside MLP profiles seem to indicate larger lateral separation in the central region of the curve than on the tangents.

4.4.6 Comparison of Mean Lateral Placement Profiles for the Before/After and North/South Curves

The MLP profiles for the BS and AS curves are presented in Figures 4.27 and 4.28. The MLP profiles for the N and S curves are presented in Figures 4.29 and 4.30. The profiles show that:

(a) The MLP profiles for the BS and AS curves (Figures 4.27 and 4.28) are different, with each profile having different locations of maximum or minimum MLP. Corner-cutting is evident in all the profiles, with the exception of the outside lane of the AS-N curve.

(b) The MLP's for the AS curves (solid lines in Figures 4.27 and 4.28) are further away from the centre-line (MLP = 0) on the inside lanes and nearer to the centre-line on the outside lanes than the corresponding MLP's for the BS curves (except for a section of the outside N curve).

(c) The lateral separation between the inside and outside profiles is noticeably larger for the AS curves than their counterpart BS curves.

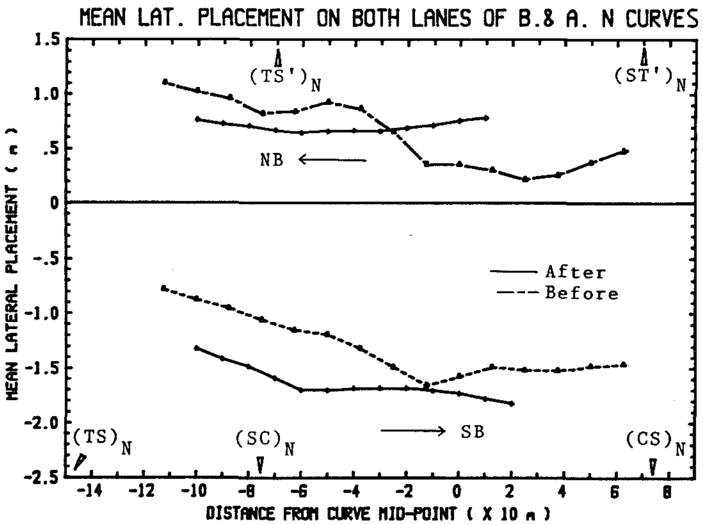

FIGURE 4.27

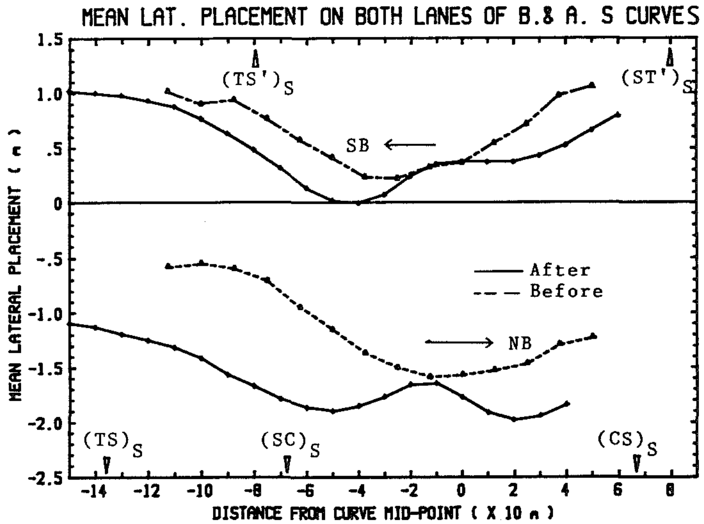

FIGURE 4.28

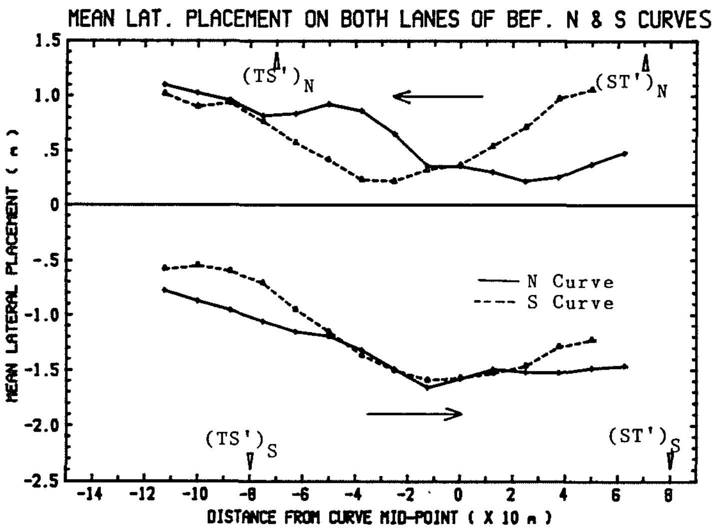

FIGURE 4.29

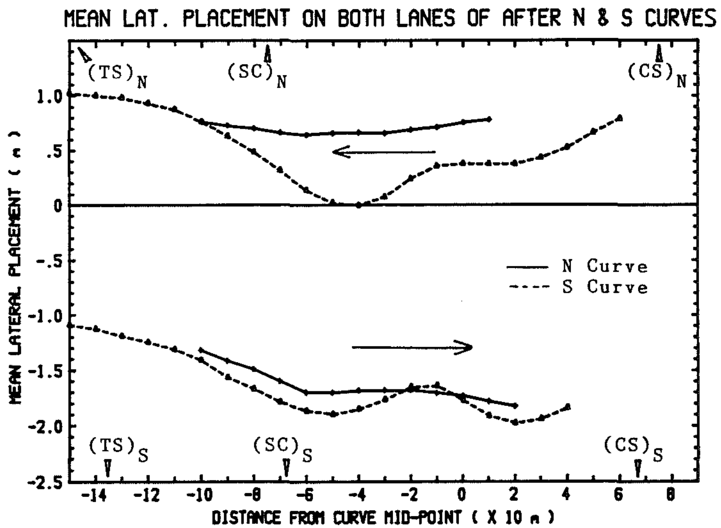

FIGURE 4.30

(d) The MLP profiles for the N and S curves for both the BS and AS curves (Figure 4.29, 4.30), shows some similarities in the inside profiles of both BS and AS curves, but very different profiles for the outside curves.

4.4.7 Mean Lateral Placement in the Central Region of the Reverse Curves

It has been pointed out in section 4.4.4 that there are no driver behaviour data for the central region of the reverse curves, and the data for the N and S curves were collected on different days. By means of combining the plots for the N and S curves, some indications of the probable average MLP behaviour at the central region can be obtained.

The combined plot for the BS curve is shown in Figure 4.31. The MLP profiles of the unobserved central section (length 63 m) between the N and S curves are hypothetically represented by dashed linear lines. The dashed lines seem to 'fit in' very smoothly between the N and S curve MLP profiles, suggesting that the data for the N and S curves are consistent. The hypothetical MLP profiles also indicate strong shifts in the MLP within the central region of the reverse curves.

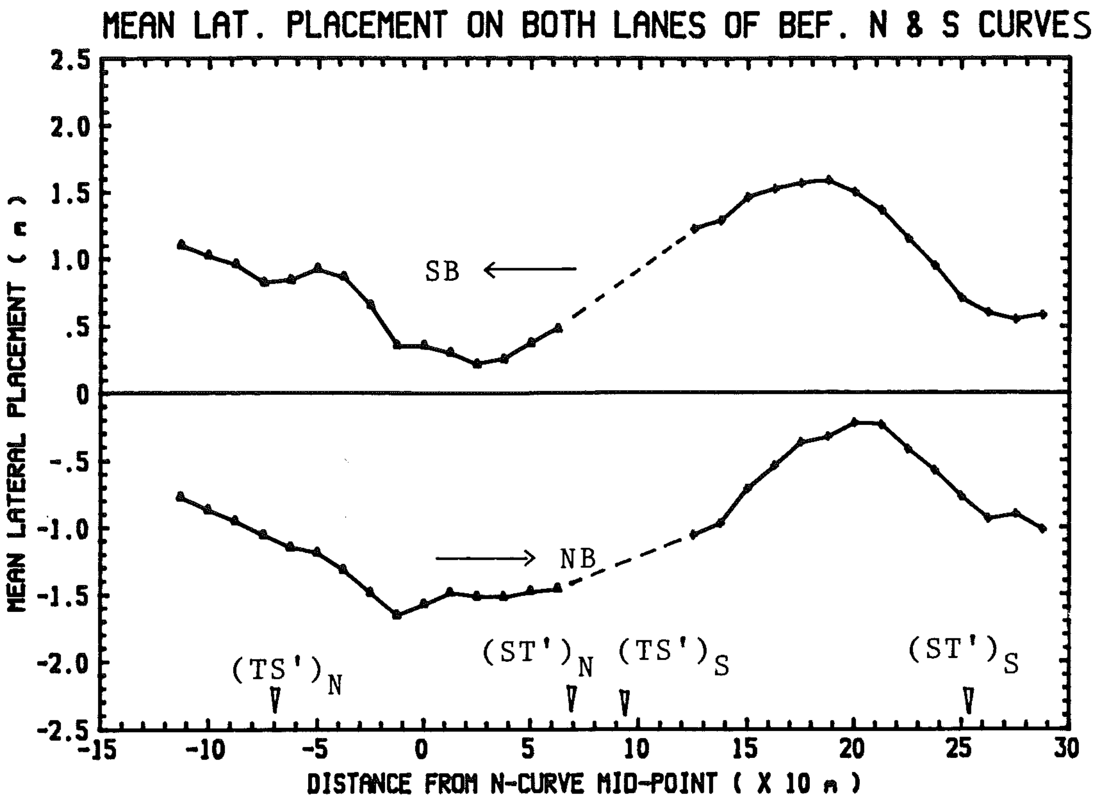

FIGURE 4.31

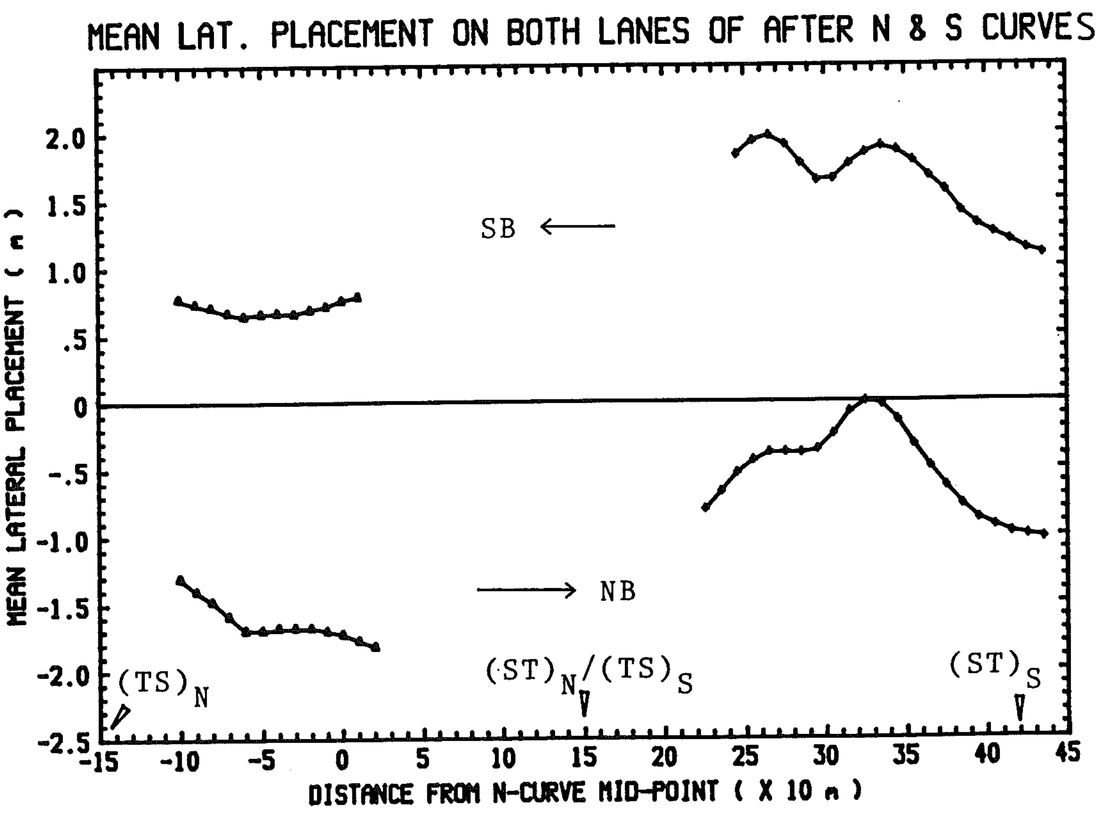

FIGURE 4.32

The combined plot for the AS curve is presented in Figure 4.32. The unobserved section within the central region is more than 200 m long, hence it is not possible to draw meaningful conclusions regarding the probable MLP behaviour within the unobserved region. However, the MLP profiles between the N and S curves appear to be compatible with each other.

4.4.8 Centrality Index

The equation describing the centrality of the subject vehicles (Sections 2.4.3.1) is restated here as follows:

$$CI = (2 \times X1 + VW - TW) / TW \quad \text{..........(4.1)}$$

where CI, X1, VW and TW are the centrality index, lateral placement, vehicle wheel span and width between selected left and right boundaries, respectively. By using the centrality index to indicate the lateral positioning of the vehicle, the reference point of the vehicle is its longitudinal axis at ground level (as compared to the reference wheel being used as the vehicle reference point in conjunction with vehicle lateral placement - see section 2.4.1).

The mean CI profiles, with the 95% confidence intervals, for the case of TW = lane width, are presented in Figures 4.33 - 4.36. The CI profiles show that:

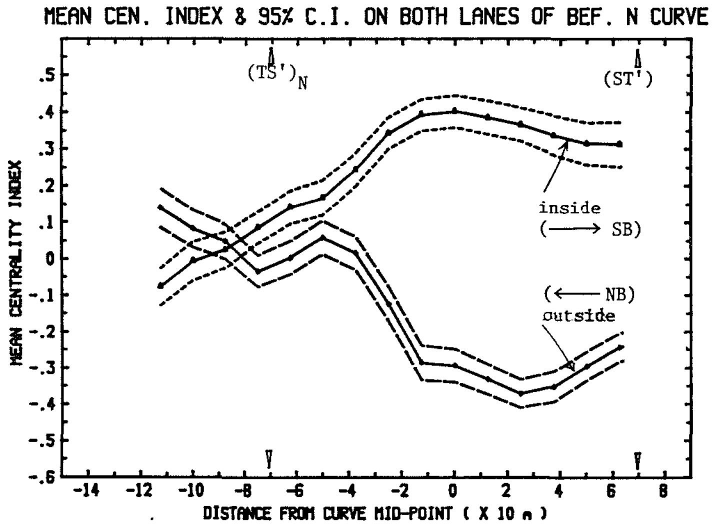

FIGURE 4.33

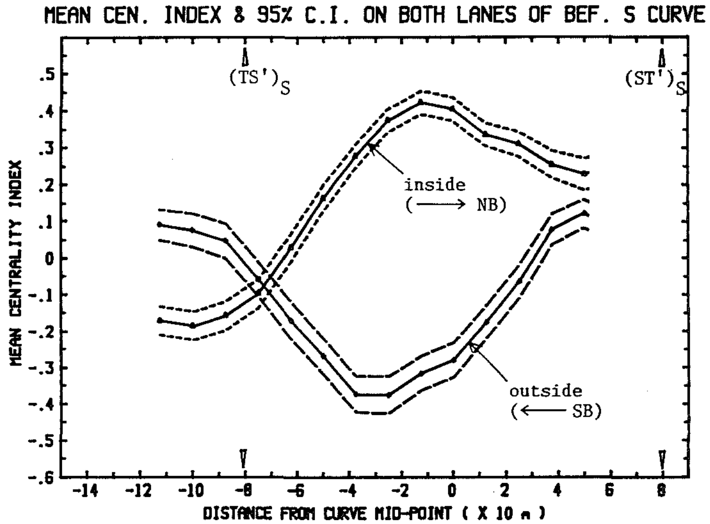

FIGURE 4.34

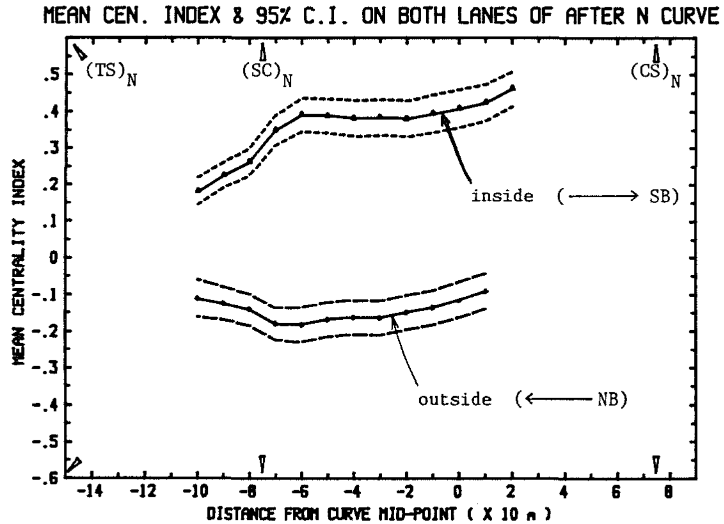

FIGURE 4.35

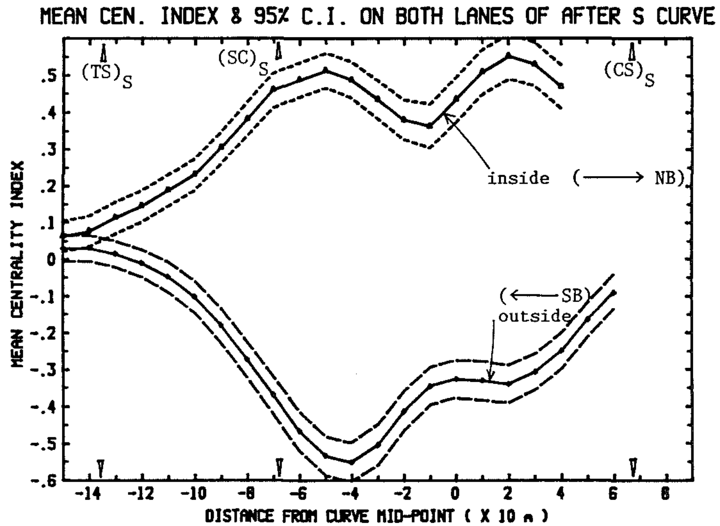

FIGURE 4.36

(a) The trends for the CI profiles are very similar to that of their counterpart MLP profiles. The close similarity in the trends is not unexpected since the lane width (TW) is fairly constant (Figures 4.3, 4.4), and equation (4.1) becomes a modified linear expression of the lateral placment X1.

(b) Vehicles on the inside lanes of the curves generally have CI > 0, implying closer proximity to the edge-line than the centre-line.

(c) Vehicles on the outside lanes of the curves generally have CI < 0, implying closer proximity to the centre-line that the edge-line.

(d) Vehicles in the vicinity of the BS curve entry points have CI < 0 on the inside lanes and CI > 0 on the outside lanes; this is the reverse of the CI values within the corresponding curves. This is consistent with a 'corner-cutting' strategy for curve negotiation, as evident from the mean lateral placement profiles (Section 4.4.5)

The CI profiles, for the case TW = lane width, for the inside and outside lanes of the BS and the AS curves, are presented in Figures 4.37-4.40. A set of CI profiles for the case TW = (lane width + sealed shoulder width) is also included, (See Figures 4.41-4.44). The CI profiles show that:

(a) Considering the inside curves (Figures 4.37, 4.39, 4.41, & 4.42), the AS CI values for the case TW = lane width are larger than the BS CI values (Figures 4.37 and 4.39); however, the AS-CI values for the case TW = (lane width + sealed shoulder width) are neither consistently less nor more than the BS-CI values (Figures 4.41 and 4.43). This implies that the realignment has resulted in a consistently more central positioning between the centre-line and the edge of seal, but not between the centre-line and the edge-line. SEE ERRATA

(b) Considering the outside curve (Figures 4.38, 4.40, 4.42, 4.44), the AS CI values, for both the cases of TW = lane width and TW = (lane width + sealed shoulder width) are larger than the BS CI values, with a larger difference for the latter case. This implies that the re-alignment has generally resulted in a less centrally positioned behaviour between the centre-line and both the edge-line and edge-of-seal.

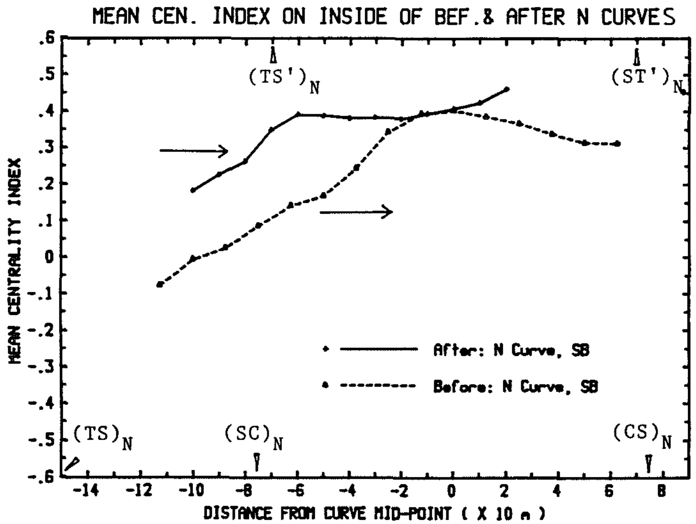

FIGURE 4.37

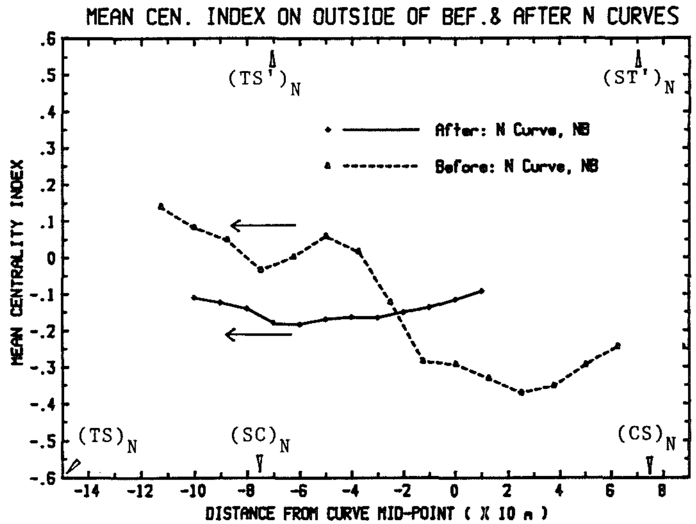

FIGURE 4.38

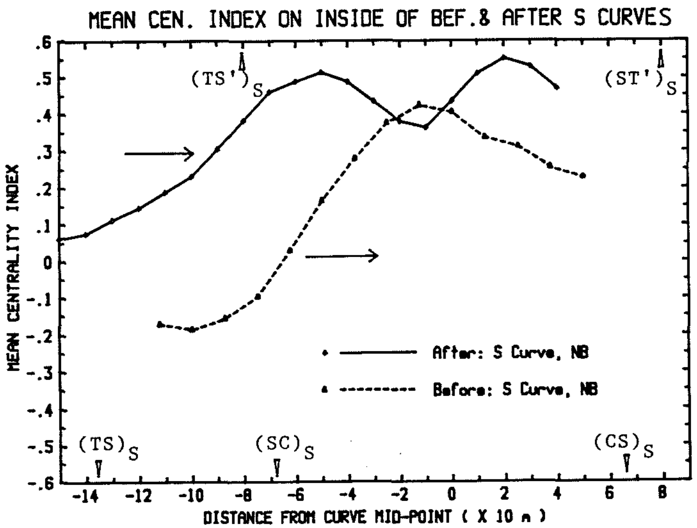

FIGURE 4.39

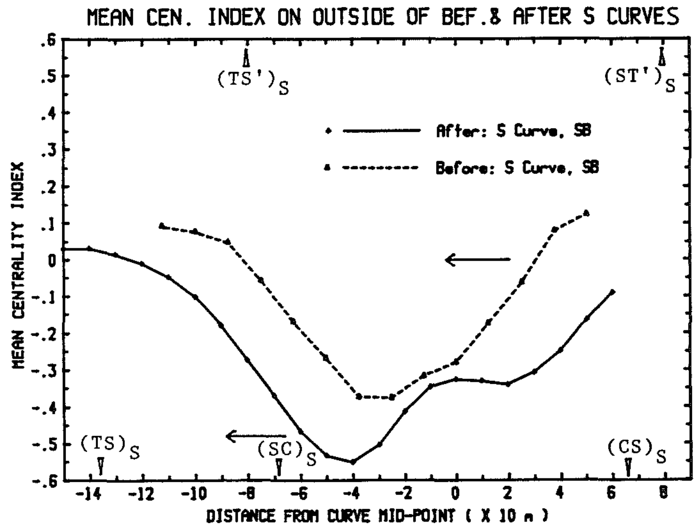

FIGURE 4.40

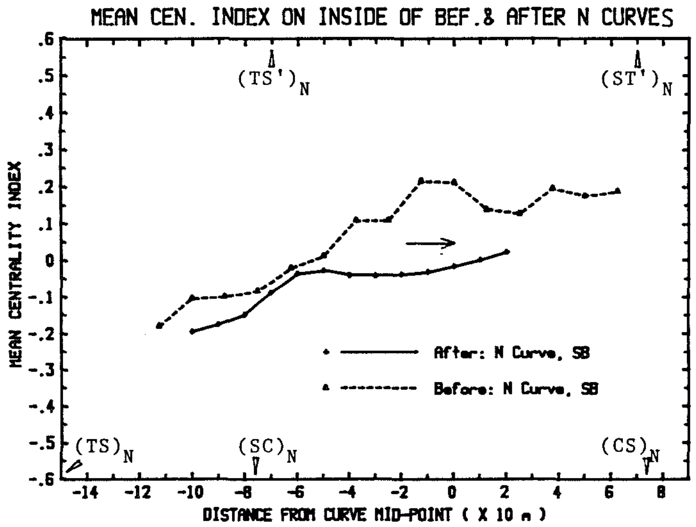

FIGURE 4.41

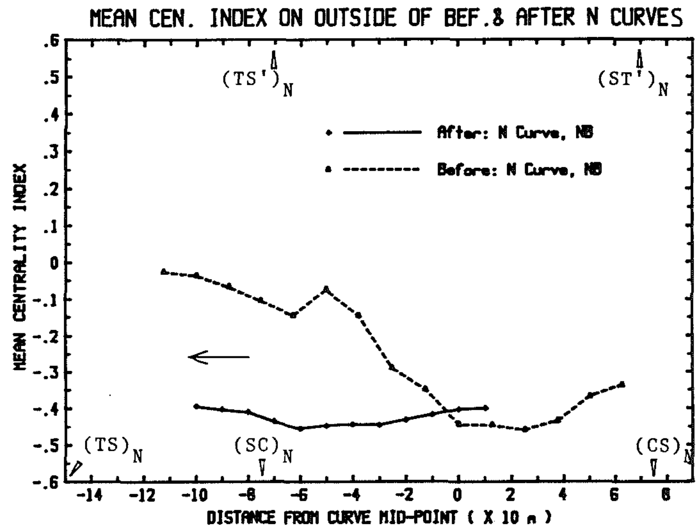

FIGURE 4.42

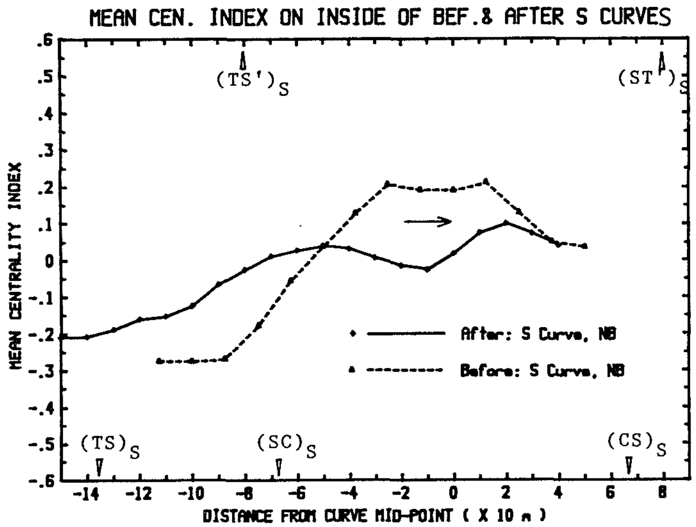

FIGURE 4.43

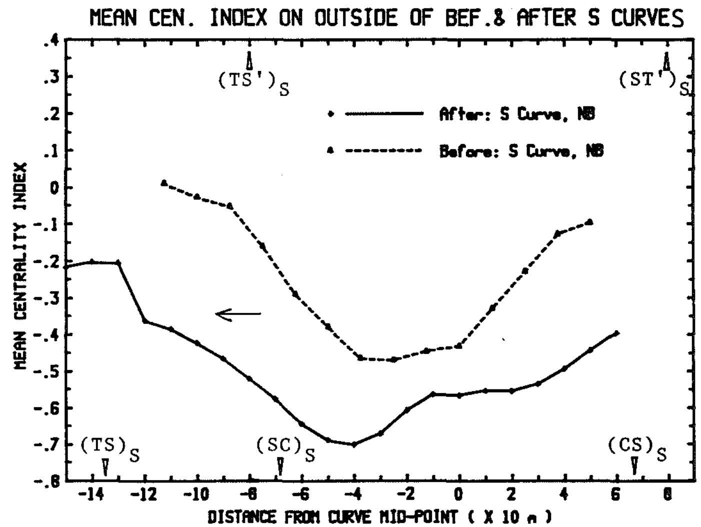

FIGURE 4.44

4.4.9 Centre-Line and Edge-Line Encroachment Profiles

The profiles showing the proportion of the sample encroaching upon the centre-line and edge-line are presented in Figures 4.45-4.52.

The encroachment profiles for the inside lanes of the BS and AS curves (Figure 4.45-4.49) show practically no centre-line encroachment within the length of curves for which data are available. In contrast, there are large proportions of edge-line encroachment within the curves, especially within the central portion of the curves. The edge-line encroachment for the AS inside curves is also generally higher than for the BS inside curves.

The encroachment profiles for the outside of the BS and AS curves (Figures 4.49-4.52) show minimal edge-line encroachment within the curves. There are relatively large proportions of centre-line encroachment for the BS outside curves; the centre-line encroachment becomes minimal for the AS-N curve but increases noticeably for the AS-S curve when compared to the corresponding BS-S curve.

CENTRE- & EDGE-LINES ENCROACHMENT ON INSIDE OF BEF. N CURVE

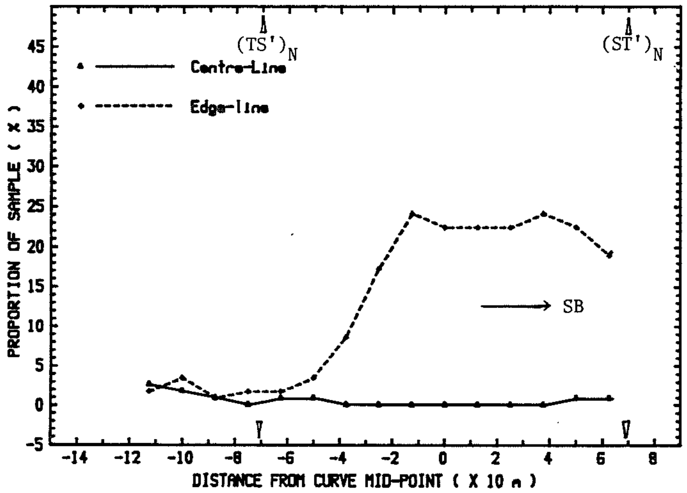

FIGURE 4.45

CENTRE- & EDGE-LINES ENCROACHMENT ON INSIDE OF AFTER N CURVE

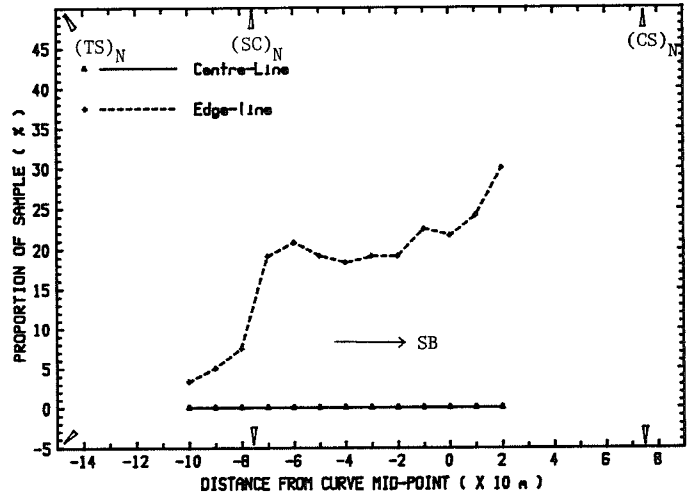

FIGURE 4.46

CENTRE- & EDGE-LINES ENCROACHMENT ON INSIDE OF BEF. S CURVE

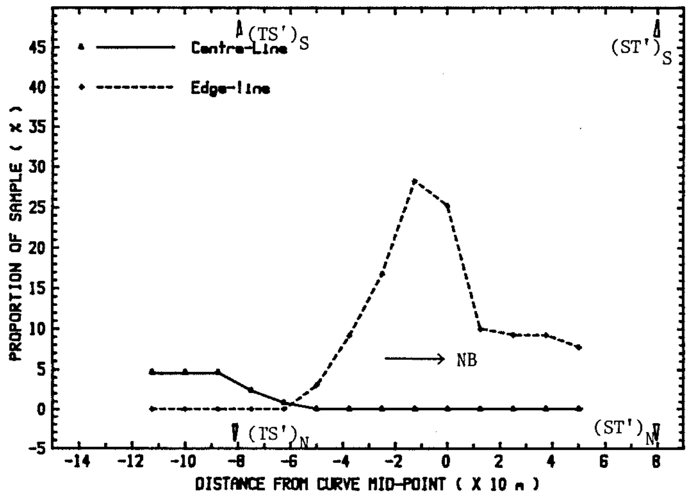

FIGURE 4.47

CENTRE- & EDGE-LINES ENCROACHMENT ON INSIDE OF AFTER S CURVE

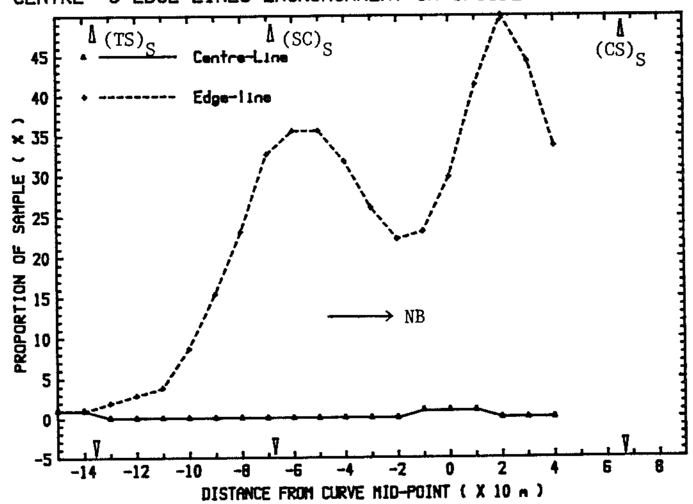

FIGURE 4.48

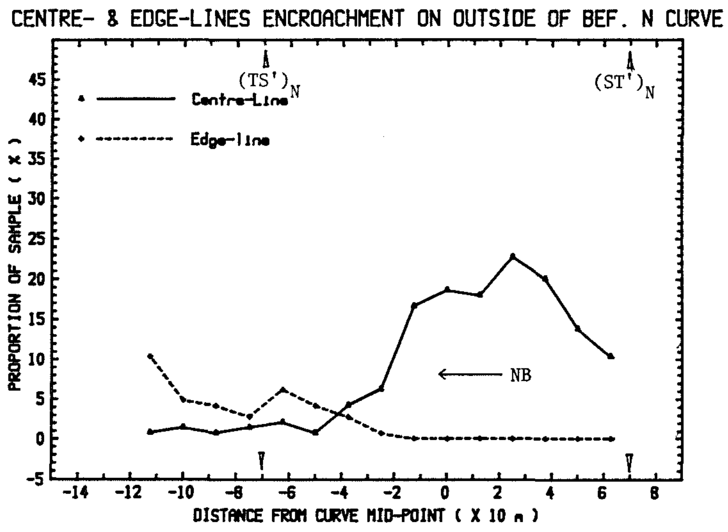

FIGURE 4.49

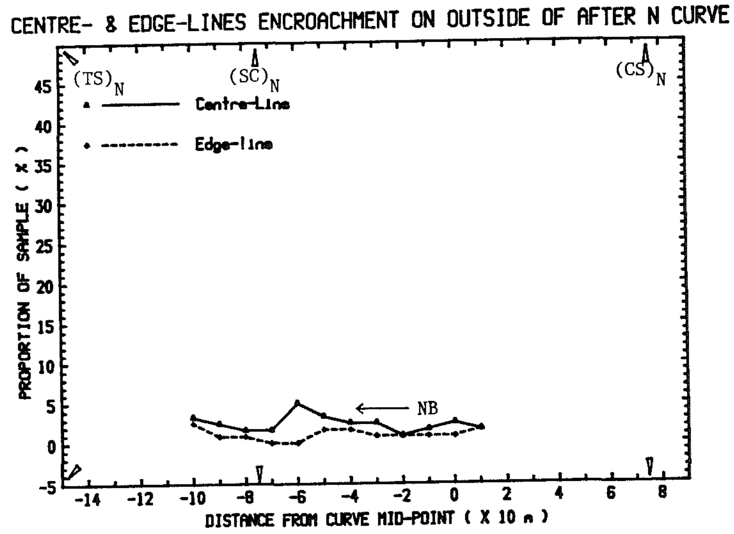

FIGURE 4.50

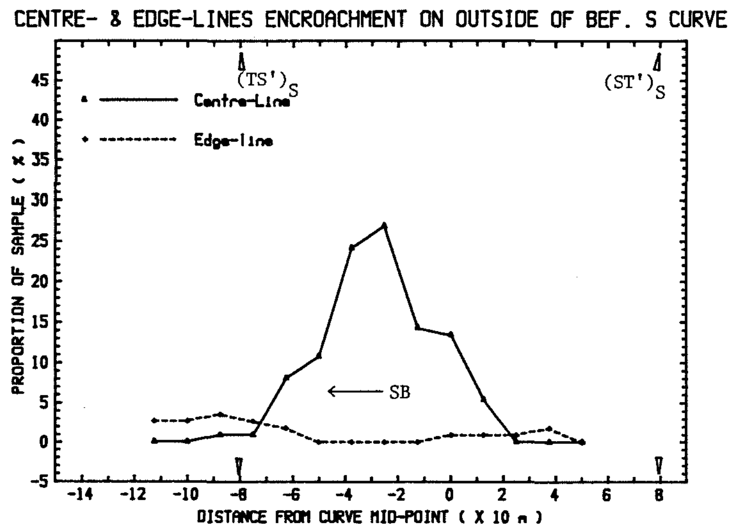

FIGURE 4.51

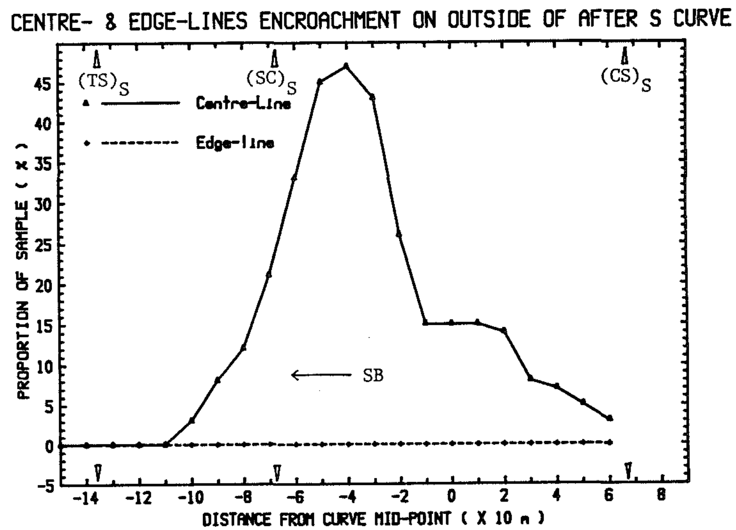

FIGURE 4.52

The proportions of vehicles encroaching on the centre-line and edge-line within the curves are as shown in Table 4.5.

Case		**Centre-line** Max.	M.P.(1)	**Edge-line** Max.	M.P.(1)
Inside	BS-N	.9	0	24	22
	AS-N	0	0	22	30
	BS-S	2.3	0	28	25
	AS-S	1	1	50	30
Outside	BS-N	23	19	6.2	0
	AS-N	5	2.5	2.5	.8
	BS-S	27	13	2.	1
	AS-S	47	15	0	0

Note: (1) At curve mid-point

Table 4.5 <u>Proportion Encroaching on Centre-line and Edge-line.</u> SEE ERRATA

4.5 BEHAVIOUR AT THE CURVE MID-POINTS

The lateral placement, speed, path radius and required sideway force coefficient at the curve mid-point are discussed in the following sections.

4.5.1 Lateral Placement

The cdf plots in Figures 4.53 and 4.54 show the lateral placement distributions at the mid-point of the curves. The lateral placement for the inside curve is plotted on a negative scale, hence the lateral separation is represented by the horizontal interval between the respective inside and outside profiles. The profiles show that, at the curve mid-point, the mean lateral separation in the AS curves has increased, especially in the AS-N curve. The mean and standard deviation of the lateral placement were as shown in Table 4.6

Case		Mean	Standard Deviation
N	Inside BS	1.57	0.40
	Outside BS	0.36	0.44
	Inside AS	1.73	0.49
	Outside AS	0.73	0.49
S	Inside BS	1.57	0.31
	Outside BS	0.36	0.40
	Inside AS	1.77	0.56
	Outside AS	0.37	0.44

Table 4.6 **Lateral Placement : Mean and Standard Deviations**

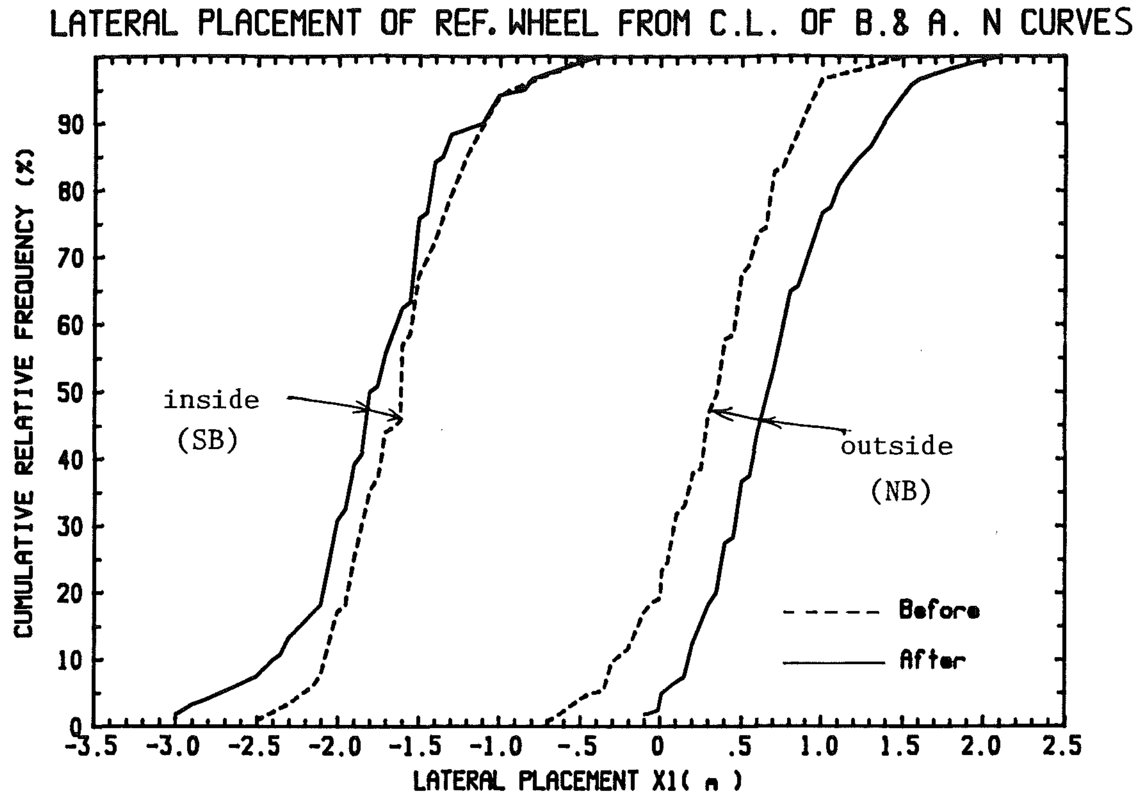

FIGURE 4.53

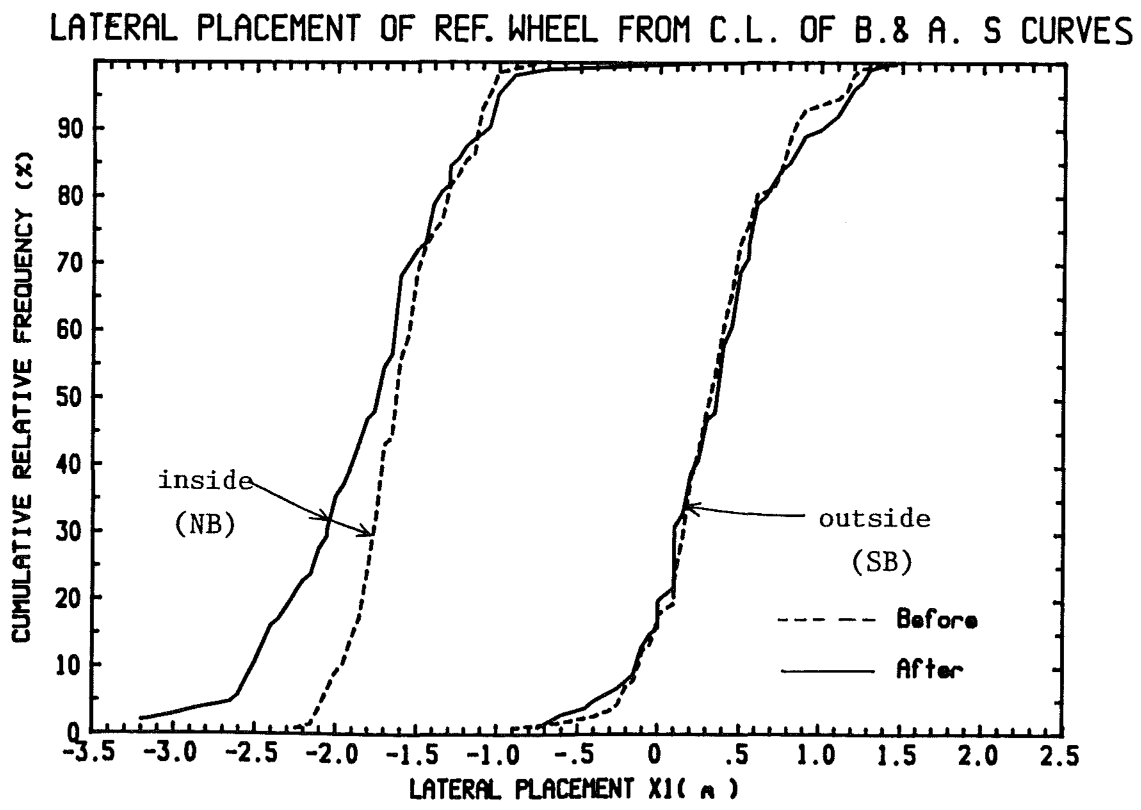

FIGURE 4.54

4.5.2 Speed

The cdf plots of speed for the BS and AS curves are as shown in Figures 4.55-4.58, while the cdf plots for the N and S curves are presented in Figures 4.59-4.62.

Comparing the BS profiles with the AS profiles (Figures 4.55-4.58), there are significant increases in the mean speed at the mid-point of the AS curves (significance probability for t-test of 0.0001 for all the cases). The profiles for the N and S curves (Figures 4.59-4.62) show relatively close mean speeds, with the significance probability (p) of the t-test being as shown in Table 4.7. It is only for the outside lanes in the BS curves that a statistically significant difference is evident.

Case		Mean	Std. Dev.	P
Inside	BS-N	85.26	13.20	0.69
	BS-S	84.63	11.55	
	AS-N	96.19	14.16	0.26
	AS-S	94.24	11.81	
Outside	BS-N	82.90	9.26	0.04
	BS-S	85.47	10.92	
	AS-N	94.86	12.61	0.52
	AS-S	93.82	11.43	

Table 4.7 Speed: Mean and Standard Deviations

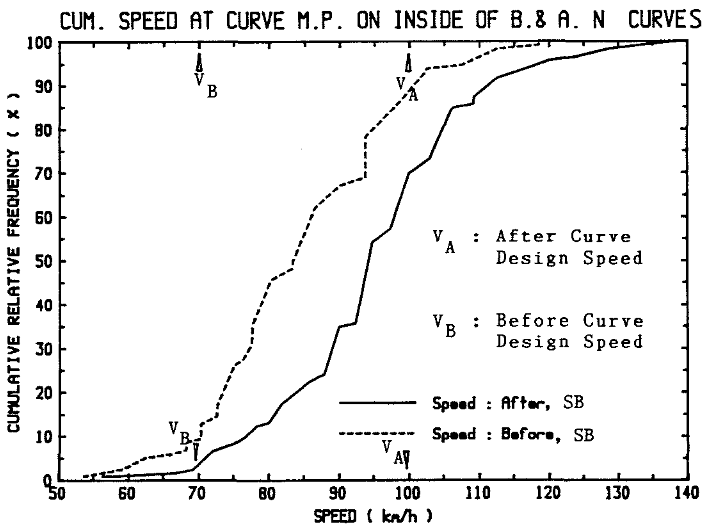

FIGURE 4.55

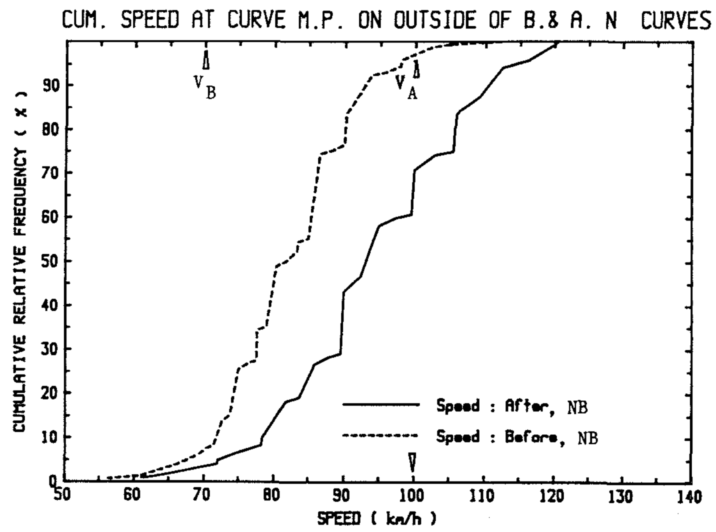

FIGURE 4.56

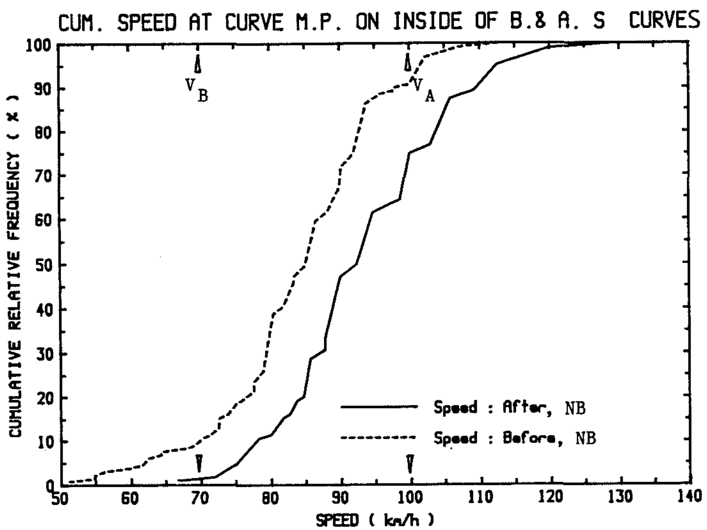

FIGURE 4.57

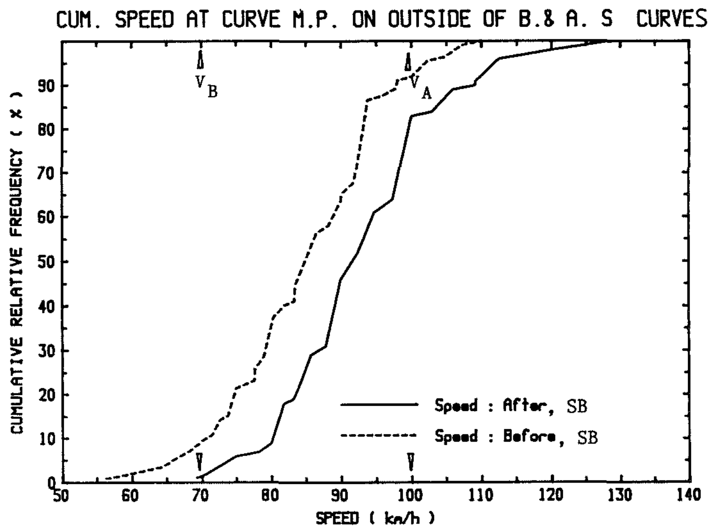

FIGURE 4.58

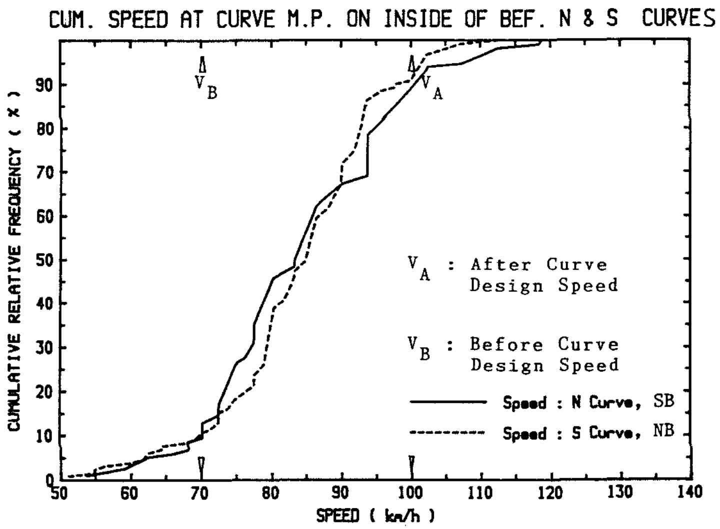

FIGURE 4.59

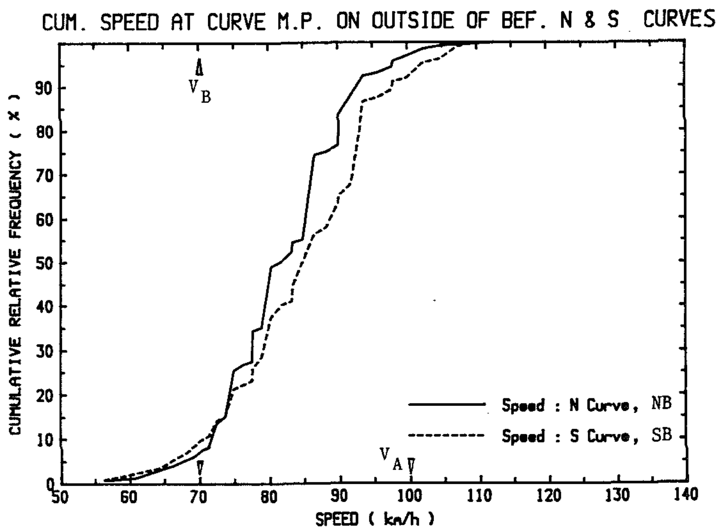

FIGURE 4.60

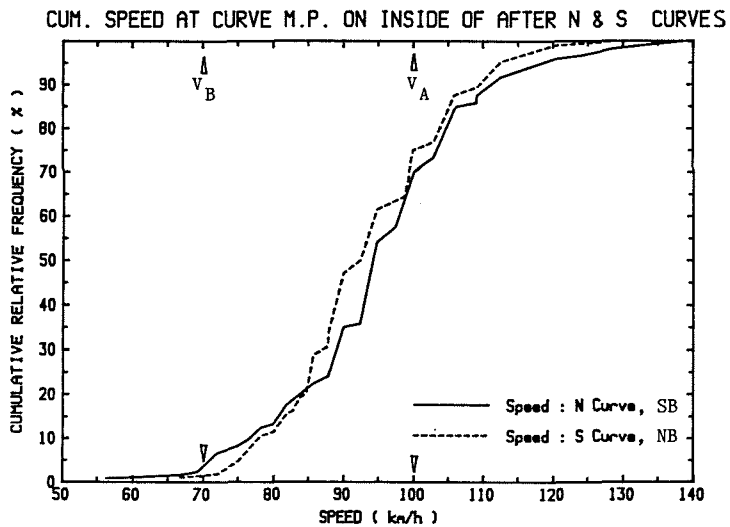

FIGURE 4.61

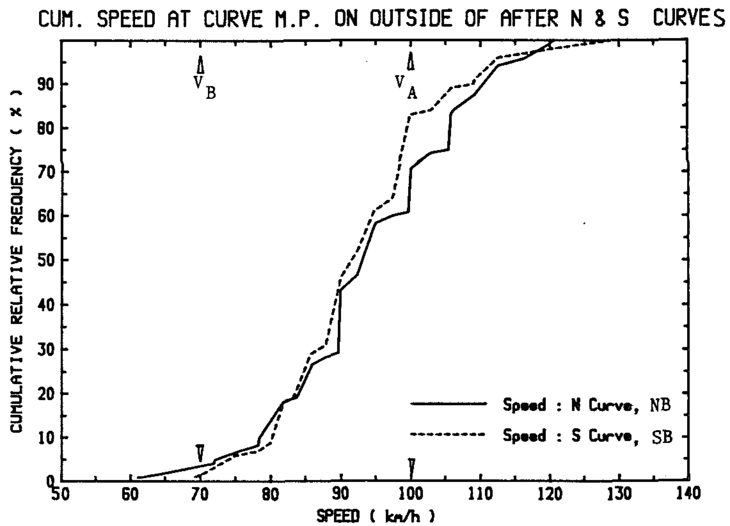

FIGURE 4.62

The proportions (%) of vehicles exceeding the advisory speed (for the BS curves) and design speed (for the AS curves) are shown in Table 4.8. It can be seen that the proportions have been much reduced by the realignment

Case	Speed (km/h)	Curve	Proportions (%)
Before	70 (advisory)	Inside - N	91
		Outside - N	93
		Inside - S	90
		Outside - S	90
After	100 (design)	Inside - N	30
		Outside - N	20
		Inside - S	25
		Outside - S	17

Table 4.8 **Proportions (%) At Curve Mid-Point Exceeding Advisory/Design Speed**

4.5.3 Wheel Path Radius

The cdf plots of the wheel path radius are shown in Figures 4.63-4.66 for the cases of BS vs AS curves and in Figures 4.67-4.70 for the cases of N vs S curves.

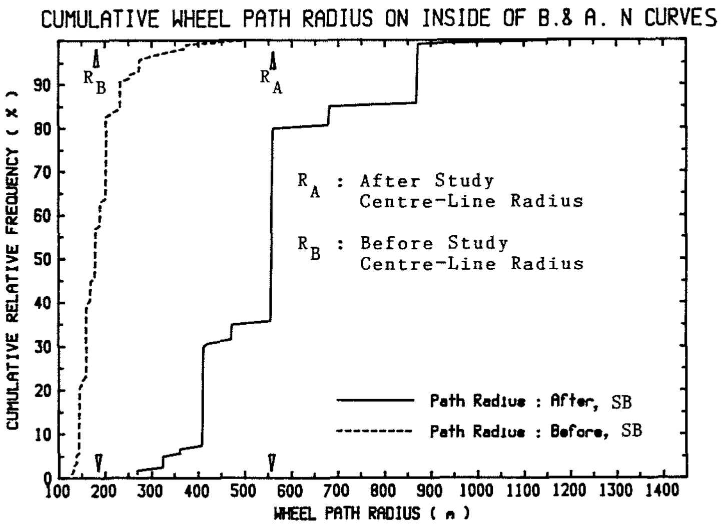

FIGURE 4.63

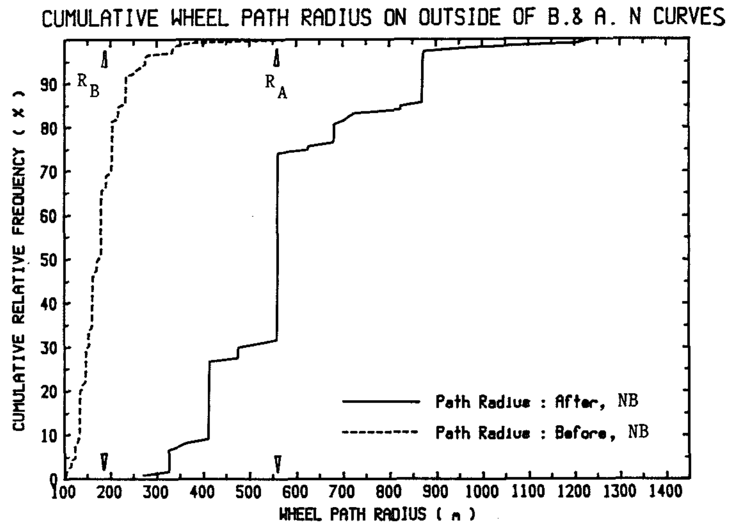

FIGURE 4.64

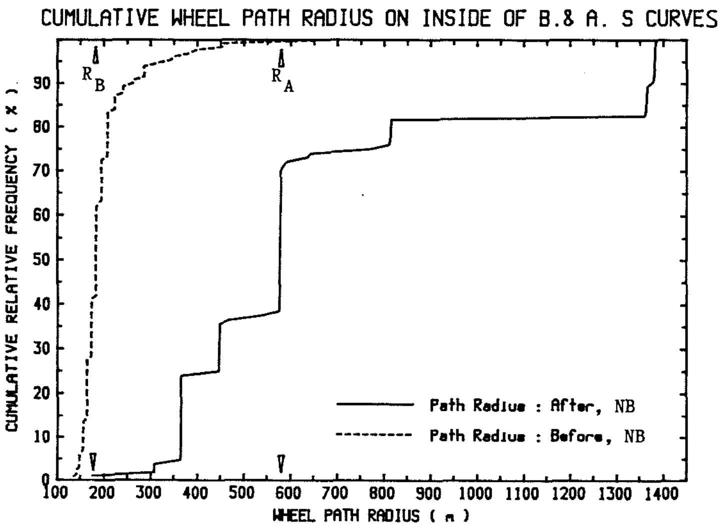

FIGURE 4.65

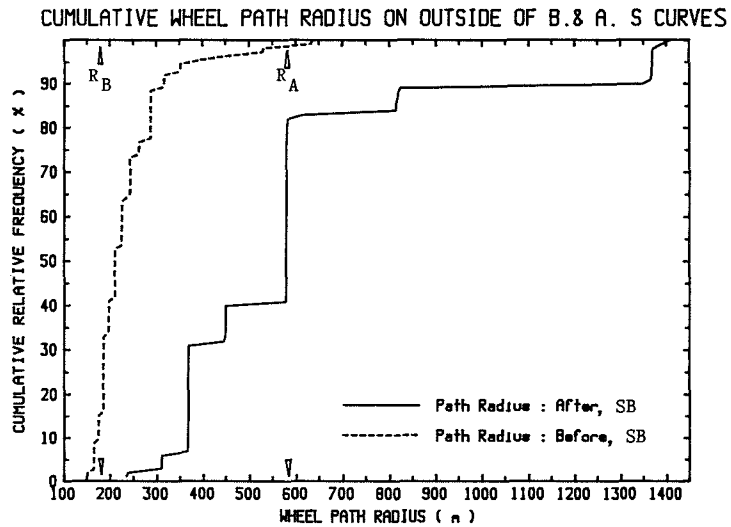

FIGURE 4.66

CUMULATIVE WHEEL PATH RADIUS ON INSIDE OF BEFORE N & S CURVES

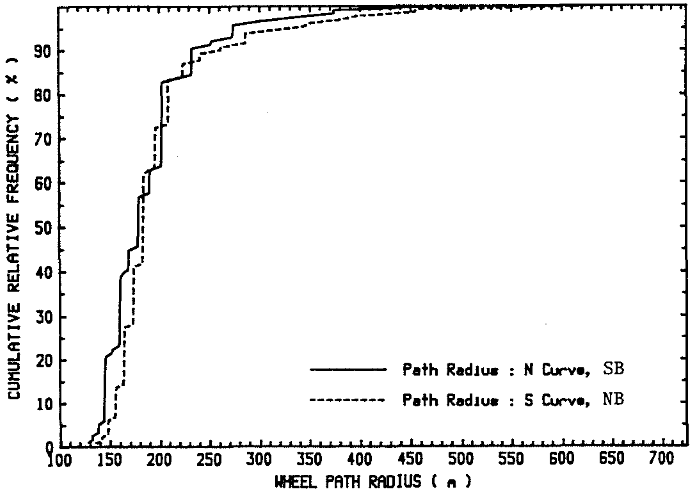

FIGURE 4.67

CUMULATIVE WHEEL PATH RADIUS ON OUTSIDE OF BEF. N & S CURVES

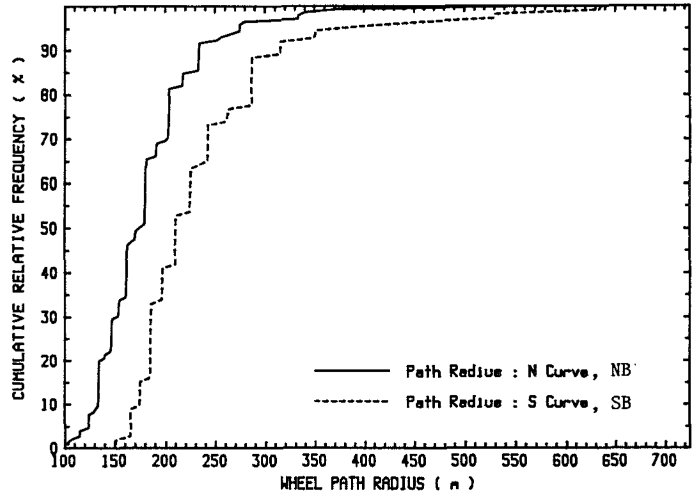

FIGURE 4.68

CUMULATIVE WHEEL PATH RADIUS ON INSIDE OF AFTER N & S CURVES

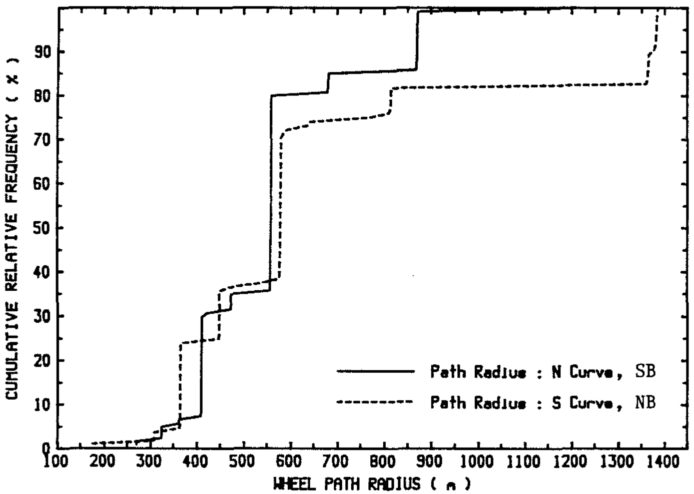

FIGURE 4.69

CUMULATIVE WHEEL PATH RADIUS ON OUTSIDE OF AFTER N & S CURVES

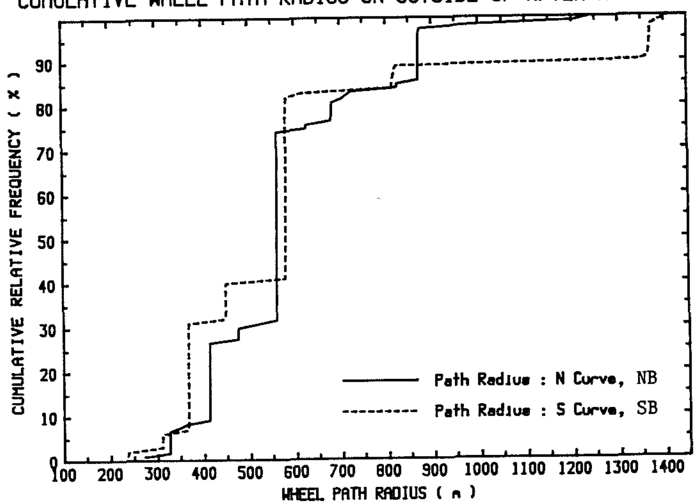

FIGURE 4.70

The BS vs AS plots (Figures 4.63-4.66) show significantly greater wheel path radii for the AS curves (t-test significant probability of 0.0001 for all the cases). The wheel path radius for the cases of the N vs S curves show lesser differences, with the significance probabilities being as shown in Table 4.9.

Case		Mean	Std. Dev.	P
Inside	BS-N	189	53.3	0.16
	BS-S	200	67.4	
	AS-N	559	166.5	0.002
	AS-S	671	356.9	
Outside	BS-N	183	57.9	0.0001
	BS-S	238	86.0	
	AS-N	580	179.1	0.56
	AS-S	599	302.0	

Table 4.9 Wheel Path Radius: Mean and Standard Deviations

The proportions (%) of wheel path radii less than the centre-line radius at the curve mid-point are shown in Table 4.10. It is noted that there was an increase in this proportion (except for the outside North curve) in the post-realignment curves.

Case	Centre-line Radius (m)	Curve	Proportion (%)
Before	180	Inside - N	57
	180	Outside - N	50
	185	Inside - S	62
	185	Outside - S	16
After	560	Inside - N	80
	560	Outside - N	36
	580	Inside - S	70
	580	Outside - S	54

Table 4.10 Proportions (%) Less than Centre-Line Radius

4.5.4 Relationship Between Speed and Path Radius

The relationship between the speed and vehicle wheel path radius was examined by computing the correlation coefficient for the best-fit linear relationship between speed and path radius. Two typical scatter plots (one for BS, one for AS) are shown in Figure 4.71 and 4.72. The correlation coefficients for the curves are as shown in Table 4.11.

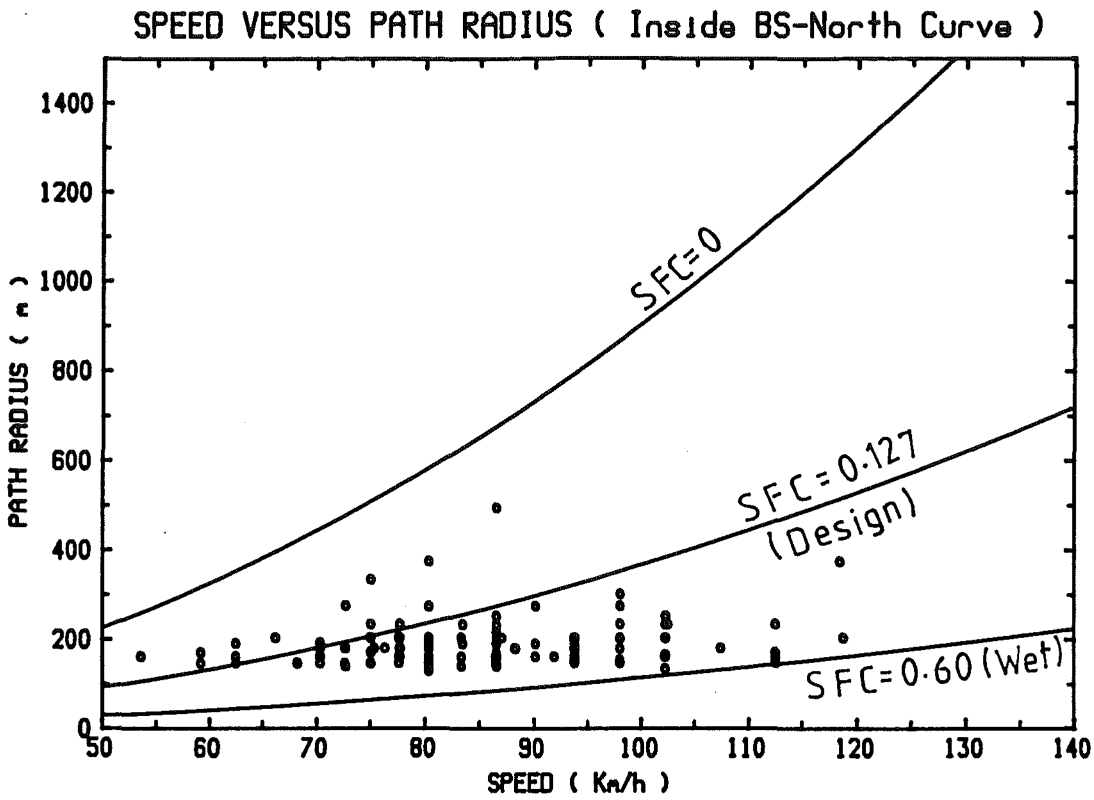

FIGURE 4.71

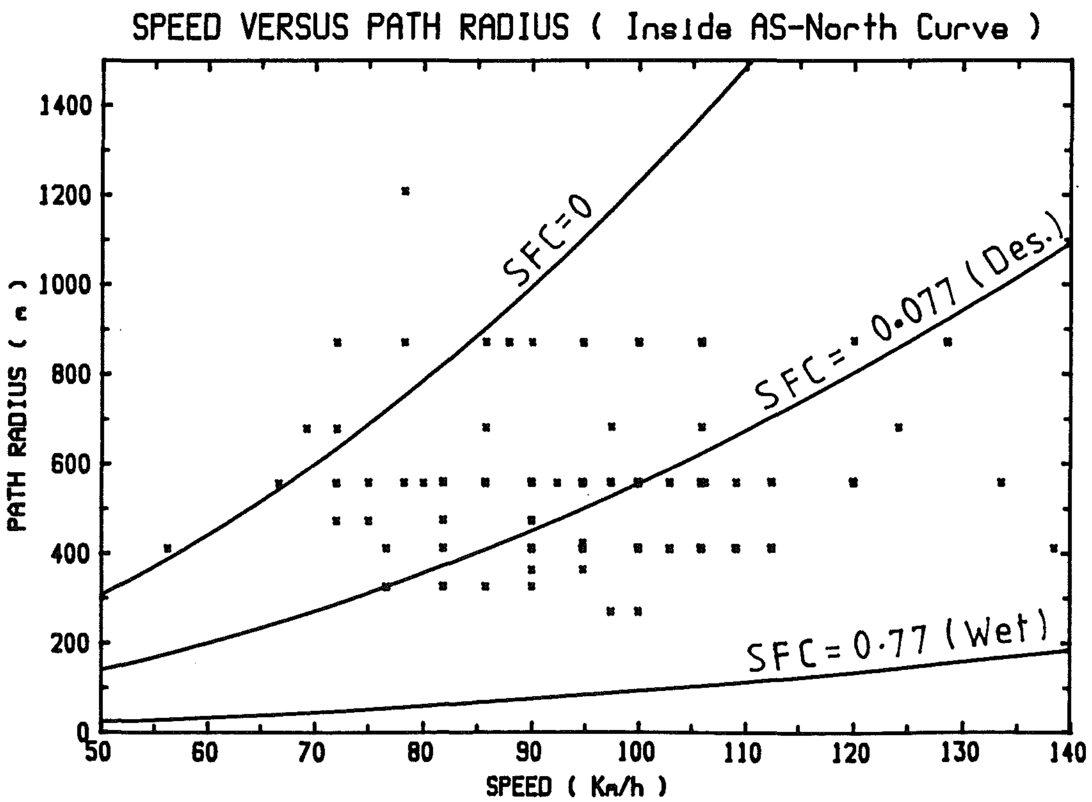

FIGURE 4.72

Case	Curve	Correlation Coefficient
Before	Inside - N	0.20
	Outside - N	0.03
	Inside - S	0.31
	Outside - S	-0.16
After	Inside - N	0.02
	Outside - N	0.07
	Inside - S	0.11
	Outside - S	0.18

Table 4.11 Correlation Coefficient between Speed and Path Way Radius

There is no evidence to indicate that speed is linearly related to path radius. The scatter plots also show many vehicles requiring SFC greater than design SFC but none exceeding the available skid resistance as measured by a British Pendulum skid-resistance tester. It is also noted that there were quite a few subject vehicles experiencing negative SFC at all the AS curves (both inside and outside lanes) but practically none at the BS curves.

4.5.5 Required Sideway Force Coefficient SFC

The cdf plots of required SFC at the curve mid-points are presented in Figures 4.71-4.74 for the cases of BS vs AS curves and in Figure 4.75-4.78 for the cases of the N vs the S curves.

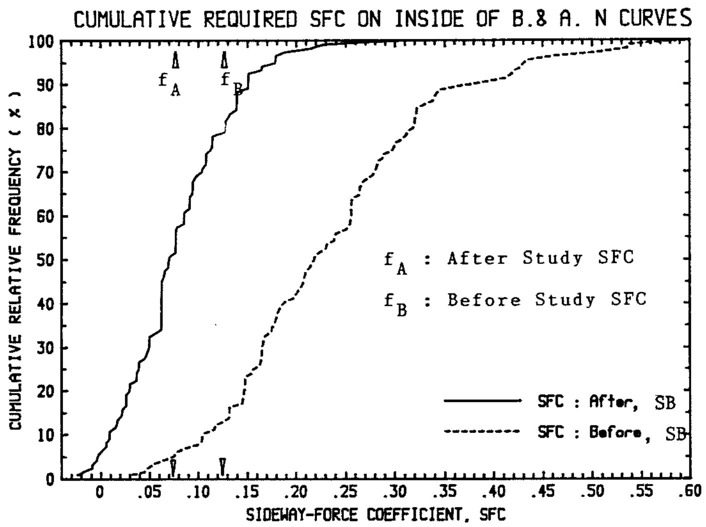

FIGURE 4.73

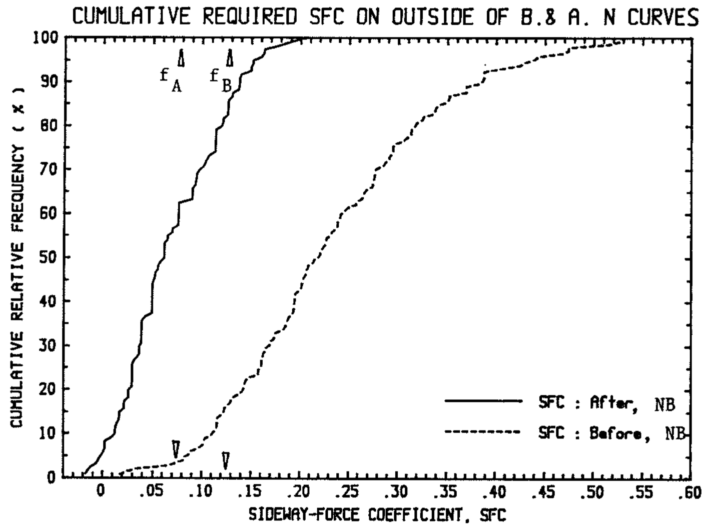

FIGURE 4.74

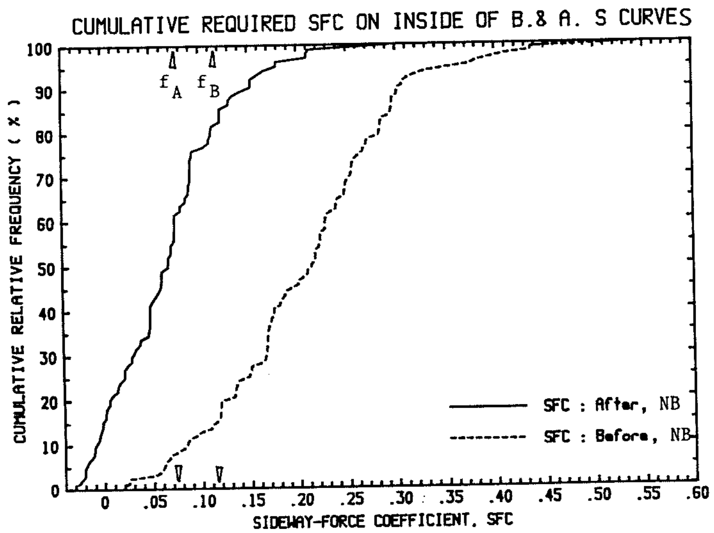

FIGURE 4.75

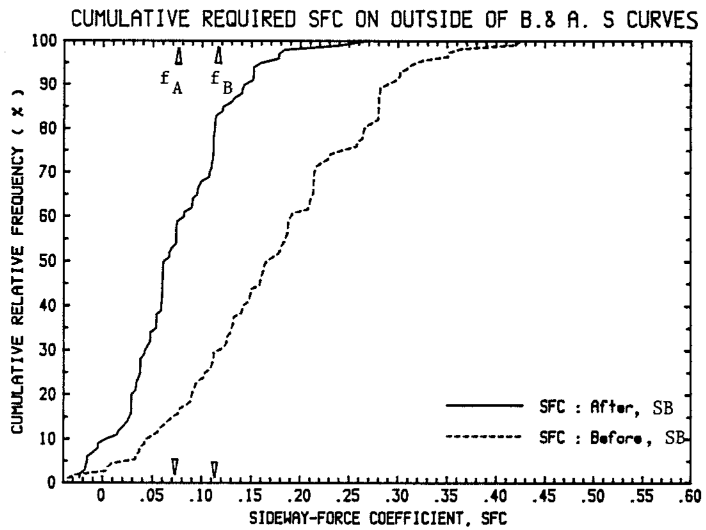

FIGURE 4.76

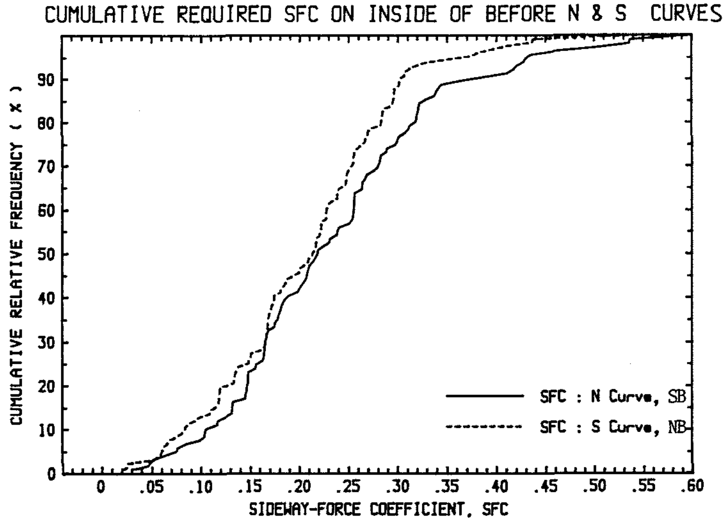

FIGURE 4.77

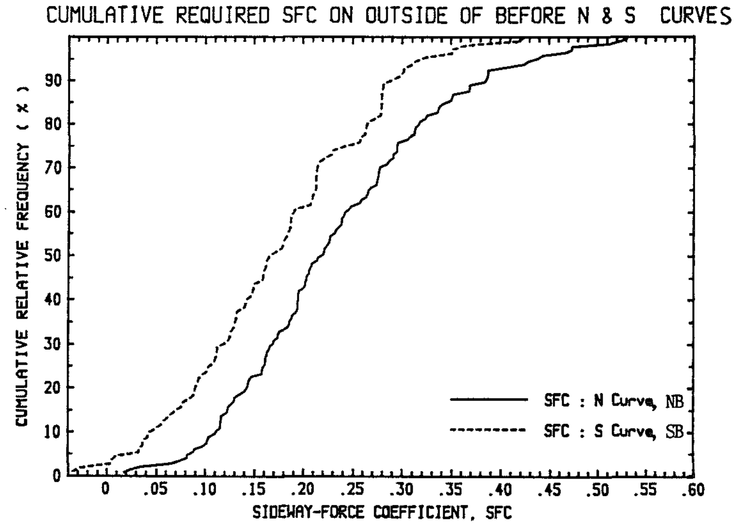

FIGURE 4.78

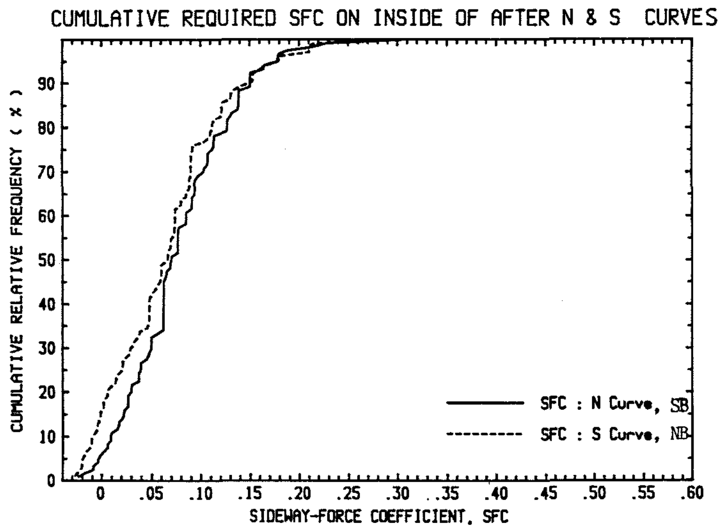

FIGURE 4.79

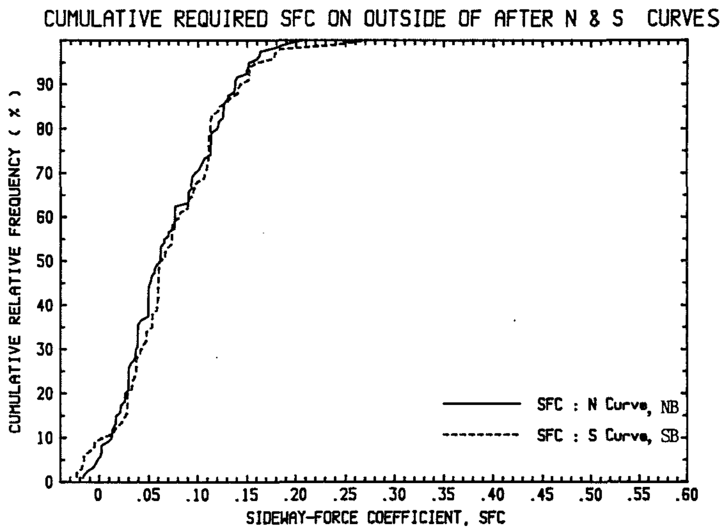

FIGURE 4.80

The BS vs AS plots (Figure 4.73-4.76) show significant and substantial reductions in the required SFC's for all the cases (t-test significance probability of 0.0001). The required SFC's for the cases of the N vs the S curves (Figures 4.77-4.80) show less differences, with the significance probabilities being as shown in Table 4.10. The mean and standard deviations of the SFC's at the curve mid-points are also shown in Table 4.12.

Case		Mean	Std. Dev.	P
Inside	BS-N	0.235	0.110	0.035
	BS-S	0.208	0.092	
	AS-N	0.079	0.056	0.13
	AS-S	0.068	0.061	
Outside	BS-N	0.235	0.107	0.0001
	BS-S	0.174	0.096	
	AS-N	0.071	0.050	0.054
	AS-S	0.075	0.055	

Table 4.12 **SFC: Mean and Standard Deviations**

The proportions (%) of the vehicles exceeding the design SFC at the curve mid-points are as shown in Table 4.13. It is evident that there was a large reduction in side friction demand at all the after-study curves.

Case	Design SFC	Curve	Proportion (%)
Before	0.127	Inside - N	83
	0.127	Outside - N	84
	0.116	Inside - S	85
	0.116	Outside - S	70
After	0.077	Inside - N	45
	0.077	Outside - N	37
	0.074	Inside - S	43
	0.074	Outside - S	42

Table 4.13 Proportion (%) Exceeding Design SFC's

4.6 ACCIDENT OCCURRENCE AT THE LEITHFIELD STUDY SITE

The Ministry of Transport file showed that in the period from 1980 to 1986 (i.e. in the 6 years prior to the realignment of the study site) there were 9 reported accidents, 8 of which could be attributed to the loss of control at the reverse curves (the ninth accident involved collision with a stationary truck which had broken down). Of the eight loss-of-control accidents, six involved south-bound vehicles and three of these resulted from loss of control at the North curve while another two could be due to initial difficulty at the North curve. Of the two accidents involving north-bound travellers, one occurred at the

South curve while the other one lost control at the departure of the North curve. Thus it appears that the south-bound lane (inside lane) of the North curve was more hazardous than the other curves. This is consistent with the observation that the proportion of subject vehicles exceeding the equivalent design speed for the minimum stopping sight distance was highest for the south-bound lane of the North curve (see Section 4.4.3.3). This suggests that monitoring the speed behaviour at locations of minimum SSD could possibly provide some indication as to the accident potential at the location.

Two other sources provided confirmation of the high level of accident occurrence at the reverse curves before realignment. Discussion with highway maintenance workers from Amberley revealed that the roadside delineator posts at the reverse curves were knocked down very frequently (the comment was 'have to fix them every week or so'). The shape of the fenceline on the east side of the reverse curves also suggested frequent battering; an interview with the property owner confirmed that the battered condition of the fence was due to the frequent lost-of-control accidents. There have however been no reported accidents for the AS curves in the post-realignment period of nearly 3 years.

4.7 SUMMARY OF RESULTS

The following are the major conclusions as a result of the study of the Leithfield Reverse Curves.

(a) Every curve has its own characteristic mean speed and mean lateral placement profiles; hence the need to be careful in generalising the results.

(b) There are some consistent results to support the suggestion that the speed profiles are influenced by the nature of the view ahead from within the reverse curves.

(c) The mean lateral placement behaviour seems to be influenced by major variations in the roadway width.

(d) The rate of change in the mean speed and mean lateral placement tend to be more substantial for the portions of the curves adjoining the long tangents.

(e) There is evidence of varying mean speed along the curves (including circular sections).

(f) There is evidence of wheel path radii differing substantially from centre-line radii.

(g) The relationship between the mean lateral placement and both the mean speed and stopping sight distance is not conclusive.

(h) 'Corner-cutting' is a notable feature of the driver curve-negotiation behaviour in all the curves. Realignment has resulted in less central positioning within the width of the lane but more central positioning within the width of the seal for the inside lane (except for the outside lane).

(i) Realignment has resulted in an increase in shoulder encroachment for both inside lanes; the effect on centre-line encroachment (by outside lane traffic) is an increase for the S-curve and a decrease for the N-curve.

(j) The data for the midpoints of the curves show that:

- realignment has resulted in a significant increase in the mean speed and wheel path radii, and a significant decrease in the required SFC's. There is also some evidence of greater lateral separation for the AS curves;

- the proportions of vehicles in the AS curves exceeding the advisory/design speed is reduced to more than 1/3 of that for the BS curves;

- the proportion of path radii in the AS curves less than the centre-line radii has actually increased, when compared to the corresponding proportion in the BS curves, except for the outside-N curve;

- the proportion of drivers requiring an SFC greater than the design values for the AS curves is about 50% less than for the BS curves;

- there is evidence that speed is not linearly related to the vehicle wheel path radius.

(k) The level of accident occurrence at the study site is likely to have reduced. There is evidence (based on Ministry of Transport accident records and the speed behaviour at the locations of minimum stopping sight distance) that the south-bound (inside) lane of the before-study North curve is more hazardous than the other curves. This suggests that monitoring the speed behaviour at locations of minimum stopping sight distance could provide some indications of the accident potential.

(l) The poor correlation between the actual mean speed behaviour and minimum stopping sight distance indicates that minimum stopping sight distance is a poor predictor of speed behaviour. The high proportion of drivers that exceeded the equivalent design speed of the minimum SSD suggests that maintaining a speed to allow for a safe SSD is of secondary importance in selecting the speed of travel.

(m) In this particular study site, the inside curves are also the first curves within the reverse curves. Hence it is not possible to establish the separate effects of the attributes of inside/outside and first/second curves.

CHAPTER V

5.1 SUMMARY OF RESULTS

5.1.1 DRIVER BEHAVIOUR AT THE STUDY CURVES

The speed profiles indicate a varying mean speed within the curve. The pattern is generally one of a deceleration followed by an acceleration. The deceleration-and-acceleration trends observed for all the curves suggest that drivers have a natural tendency to slow down when entering any horizontal curve. A large proportion of vehicles exceeded the advisory speed (70 km/h) for the low standard curves. A direct relationship exists between the proportion of vehicles exceeding the curve safe speed and the difference between the tangent operating speed and the curve safe speed. Higher operating speeds within the curves are also associated with larger curve radii. These findings are consistent with the findings of McLean (1976, 1978) that the curve operating speeds are related to the tangent operating speed and curve radius.

The results show that the minimum mean speed is not always at the mid-point of the curve. This highlights the importance of not considering speed behaviour only at the curve mid-point. The speed profile is also not symmetrical. The approaching deceleration rate tended to be less than the departure acceleration rate at the Foremans Road curve. The trends in the speed profiles at the Leithfield reverse curve seemed to be very much influenced by the nature of the view ahead (the amount of sight distance ahead, the presence of the second curve, and the ease of perceiving the second curve).

The reconstruction work along one of the adjoining tangents at the Foremans Road curve seems to have influenced the operating speed in the downstream section of road. The increase in the operating speed environment along the reconstructed tangent was likely to have affected the approach speed of the follow-on curve.

The speed behaviour at the point of minimum sight distance for the Leithfield curves before realignment showed a very high proportion of vehicles exceeding the safe speed based on stopping sight distance, suggesting that maintaining an adequate stopping sight distance seems to be of secondary importance. It was found that at the study curves, the speeds at the point of minimum sight distance were not strongly related to the minimum sight distances (i.e. the speed was not always lower for those curves with a lower minimum sight distance). The curve with the higher proportion of vehicles exceeding the safe stopping sight distance did have a higher proportion of accidents.

Each curve had its own distinctive speed profile. Even the inside lanes of the Leithfield North and South curves, and the outside lanes, had different speed profiles.

The lateral placement and encroachment profiles show that corner-cutting is a common phenomenon, which is mainly limited to within the bounds of the curve. Lateral placement profiles seem to be influenced by major variations in the roadway width. The lateral separation at the curve mid-point did not change as a rsult of realignment. SEE ERRATA

There is evidence of the wheel path radius differing substantially from the curve radius. For the smaller radius curves, a high proportion of path radii were greater than the curve radius, while for the larger radius curves, a high proportion of path radii were less than the curve radius, resulting in the overestimation of the sideway force coefficient for the smaller radius curves and underestimation for the larger radius curves. It is therefore important to make an allowance for any discrepancy between the path radius and the curve radius when estimating the sideway force coefficient. The study data also indicate no statistically significant correlation between the path radius and the speed at the mid-point.

5.1.2 RESULTS OF CURVE REALIGNMENT

The factors that were studied and are indicative of the level of safety of the curves are the centre-line and shoulder encroachment patterns, the proportion of vehicles exceeding the design speed value, the proportion of path radii less than the geometric radius and the required side friction (sideway force coefficient). In addition, accident statistics could be used if a sufficient length of time were allowed for the 'after' period.

Encroachment patterns are related to safety in that centre-line encroachment would tend to increase the probability of head-on collisions or conflicts, while shoulder encroachment would increae the likelihood of losing control beyond the edge of the sealed pavement. The observations at the Foremans Road curve showed that there was a reduction in the proportions of vehicles encroaching upon the centre-line and the edge-line, while the encroachment patterns at the Leithfield site showed an increase in edge-line encroachment, and an increase for one curve and a decrease for the other curve in the centre-line encroachment. It should be noted that there was relatively little change in the width of the sealed pavement at the Foremans Road curve and a large increase in the sealed pavement width at the Leithfield curve, while the lane width remained relatively constant at both sites.

The proportion of vehicles exceeding the design speed or with a path radius less than the geometric radius are not good indicators of the margin of safety if each is considered on its own. It is clear that there is a range of combinations of speed and path radius that give rise to a particular level of side friction requirement. Hence a high speed vehicle with a path radius much larger than the geometric radius may safely negotiate a curve with a sideway force coefficient less than the 'safe' (or available) value.

However, the speed and path radius can be used for estimating the required side away force coefficient On this basis, the realignment of Foremans Road curve has resulted in a reduction in the required SFC's on the inside lane and an increase on the outside lane. The available SFC was increased substantially (measured at the time of study), and thus there was an overall increase in the margin of safety (the difference between the available and the required side friction), though this net increase was a lot less for the outside curve than the inside curve. The required SFC's at the Leithfield study site were all considerably lower in the curves after realignment.

The concept of risk compensation has been discussed in Chapter I (Section 1.5). It can be seen that there is some evidence of drivers experiencing a higher side-thrust on the outside lane but a lower side-thrust on the inside lane for the realigned Foremans Road curve. In terms of the degree of side-thrust experienced, there is both positive and negative risk compensation, depending on the direction of travel. However, if the margin of safety is considered, there was on the whole a trend towards a gain in the level of safety. This was also the case for the Leithfield study site.

The scope for risk compensation at the Leithfield study site was constrained. The tangent operating speed did not change due to the realignment (i.e. there was no change in the operating speed environment in the vicinity), but the curve safe speed increased due to the realignment. Hence, the difference between the tangent operating speed and the curve safe speed decreased. It can therefore be argued that there was little scope for drivers to modify their behaviour in response to the increased curve standard such that there was no net gain in safety, unless they increase speed as they approached the curve (not a natural behaviour).

The variability in the driver behaviour can be viewed as a manisfestation of variations in the level of subjective risk between and within drivers. It is unlikely that the driver can precisely determine what amount of side friction is available at a particular point at a particular time. The margin of safety (the difference between available and required side friction) can be used as an objective measure of the risk associated with the observed speed and lateral placement behaviour, which are related to the driver's perceived (subjective) risk in some (as yet) unknown way. Thus the margin of safety determined objectively from observing driver behaviour can give only limited insight into driver subjective risk.

The accident records at both study sites suggest that there has been an improvement in the safety level. This improvement in the rate of accident occurrence and the net gain in the margin of safety (the difference between the available and the required side friction), show that risk compensation does not seem to operate in the manner suggested by proponents of the risk homeostasis theory.

5.2 COMPARISON OF DESIGN ASSUMPTIONS WITH ACTUAL BEHAVIOUR

The underlying assumptions in the design of horizontal curve that have been investigated in this study are:

(a) the operating characteristics are the same for both the inside and outside lanes of the curve;

(b) most of the drivers traverse the curve at or below the design speed;

(c) drivers maintain a constant speed along the length of the curve;

(d) drivers follow a path (or trajectory) with a radius equal to the geometric radius of the curve (transitions and circular arc).

Assumptions (c) and (d) are explicit, and are part of the mechanics of curve design, while (a) and (b) are implicit. The validity of each of these assumptions is examined in the light of the empirical results obtained during this study.

The empirical results amply demonstrate that the inside and outside lane of a curve each has its own characteristic mean speed and mean lateral placement profiles. It is therefore not adequate to study only one lane.

The proportions of sample vehicles exceeding the advisory speed was very high for the before-realignment curves (about 90% or more in most cases at the curve mid-point). Between a tenth and a third of the vehicles exceeded the design speed of the curves after realignment at the curve mid-point. The high proportion of vehicles exceeding the advisory speed was probably due to the the high operating speed environment (the proportions were higher for the Leithfield study site where the operating speed was also higher) and the driver experience of safely negotiating other curves in the vicinity (or the road network in general) at speeds substantially greater than the posted advisory speeds. The mean speed profiles from the study sites indicate substantial variations in the mean speed values along the whole length of the curve in most cases; where there was a region of constant speed, it tended to be centered at a point before the mid-point of the curve. Therefore, the use of a common speed value for coordinating the elements of a horizontal curve does not appear to be completely and universally justified.

The mean lateral placement profiles for all the study curves show strong lateral shifts in a manner indicative of a 'corner-cutting' strategy. For lateral shifting to occur it is theoretically necessary for the path radius to be smaller than the roadway radius at some location along the length of the curve or in the adjoining tangents. It seems that the phenomenon of the path radius being smaller than the geometric radius usually occurred before curve entry but there was some indications in some of the after realignment mean lateral placement profiles that this phenomenon also ocurred within the curve (viz. the bi-modal shape of some mean lateral placement profiles). There was no evidence of the path radius being equal to the geometric radius for a substantial length of any of the curves.

The empirical results show that none of the underlying assumptions of driver behaviour as currently adopted by the road designers and tested in this study, is completely valid at the curves that were studied.

The particularly high proportions of vehicles exceeding the advisory speed for the curves before realignment and the much lower proportions after realignment point to the importance of adopting a realistic speed for design. The philosopy of choosing a design speed to coordinate a curve element with the general operating speed environment in the vicinity (as recommended by NAASRA, 1980) seems to be more appropriate than adopting a design speed based on the prevailing topography and class of road (as recommended by AASHO, 1954).

The speed and lateral placement profiles were shown not to be symmetrical about the mid-points of the curve nor were their minimum mean values always occurring at the curve mid-point. The location of the critical point of the curve (i.e. the point at which the combination of speed and path radius gives a maximum SFC requirement) is yet to be clearly identified. The critical point can be located from the distribution of sideway force coefficient (SFC) at various points along the curve. The distribution of SFC at a point can be obtained from analysis of the interaction between the speed and path radius of each individual vehicle, or can be estimated from the probability distributions for the speed and path radius (by means of simulation methods, such as the Monte Carlo method). If such analyses were carried out over a range of curves it would be possible to devise general rules for curve design based on the critical point in the curve. This information could be used as a basis for general curve design.

5.3 CONCLUSION

The method of continuous video-recording of vehicles moving through the study curve was found to be suitable for the study of normal driver behaviour. However it must be emphasised that there is considerable scope for improving the efficiency in the data extraction process (which was carried out manually in this study) by making use of the advances made in the field of image processing. It is anticipated that video recording in association with image processing would allow a similar study to be carried out at a range of horizontal curves. This would give a better knowledge of normal driver behaviour at curves and provide the road designer with a validated set of assumptions of driver behaviour for use in road design. A more safe road network should result.

The before and after study at the realigned curves has shown that the speed and lateral placement data can be used to estimate the required sideway force coefficient; the difference between the available SFC and required SFC can be used as an objective measure in evaluating the realignment, by giving an estimate of a change in the margin of safety. The driver behaviour was also examined and comparison was made between the before-study and after-study curves. The underlying design assumptions were checked and shown not to be completely and universally valid.

The realignment work resulted in an improvement in the margin of safety at most of the curves. For the case of the Foremans Road outside curve, an increase in the required SFC was observed, though there was a net gain in the margin of safety due to available SFC having improved by a larger factor. It is unlikely that drivers are able to accurately estimate the available SFC. Therefore the gain in the margin of safety, as measured objectively by the difference in the available and the required SFC, is unlikely to influence the drivers' choice of speed and lateral placement behaviour. The higher SFC at the Foremans Road outside curve thus indicates a negative risk compensation (though there was probably a confounding effect from the increased operating speed along the reconstructed tangent). The available SFC might well reduce with trafficking, hence if drivers continue to drive in the manner as observed, there would be a reduction in the margin of safety. Overall, the results are rather mixed; they indicate both positive and negative risk compensation, and there is a need for further research to obtain generalisable results.

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